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ABSTRACT

This teacher's guide to microgravity contains 16 student science activities with full background information to facilitate an understanding of the concepts of microgravity for teachers and students. Topics covered in the background sections include the definitions of gravity and microgravity, creating microgravity, the fluid state, combustion science, materials science, biotechnology, and microgravity and space flight. There is a curriculum content matrix to accompany the science activities that identifies which activities have applications in physics, mathematics, and chemistry. These activities include satellite motion, free fall motion and weightless effects, accelerometers, gravity and acceleration, inertial balance, gravity driven fluid flow, surface tension, fiber pulling, crystal growth, rapid crystallization, and microscopic observation of crystal growth. This guide also provides a list of relevant National Aeronautics and Space Administration (NASA) educational materials such as videotapes, slides, software, and print publications. Recommended readings from books and periodicals as well as contact information for various branches of NASA are also included. (DDR)

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MICROGRAVITY

Teacher's Guide With Activities for Physical Science

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The Cover

The National Aeronautics and Space Administration uses a variety of technologies to create microgravity environments for research. Pictured is the Space Shuttle Orbiter positioned with its tail pointed towards Earth to obtain the lowest possible gravity levels. In this orientation, called a gravity gradient attitude, the vehicle's position is maintained primarily by natural forces. This reduces the need for orbiter thruster firings that disturb acceleration-sensitive experiments.

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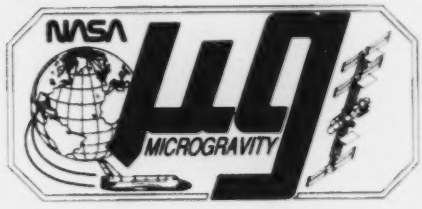
Microgravity

A Teacher's Guide With Activities
For Physical Science

National Aeronautics and Space Administration



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Introduction

There are many reasons for space flight. Space flight carries scientific instruments, and sometimes humans, high above the ground, permitting us to see Earth as a planet and to study the complex interactions of atmosphere, oceans, land, energy, and living things. Space flight lofts scientific instruments above the filtering effects of the atmosphere, making the entire electromagnetic spectrum available and allowing us to see more clearly the distant planets, stars, and galaxies. Space flight permits us to travel directly to other worlds to see them close up and sample their compositions. Finally, space flight allows scientists to investigate the fundamental states of matter—solids, liquids, and gases—and the forces that affect them in a microgravity environment. The study of the states of matter and their interactions in microgravity is an exciting opportunity to expand the frontiers of science. Investigations include materials science, combustion, fluids, and biotechnology. Microgravity is the subject of this teacher's guide.

What Is Microgravity?

The presence of Earth creates a gravitational field that acts to attract objects with a force inversely proportional to the square of the distance between the center of the object and the center of Earth. When measured on the surface of Earth, the acceleration of an object acted upon only by Earth's gravity is commonly referred to as one g or one Earth gravity. This acceleration is approximately 9.8 meters/second squared (m/s^2).

The term *microgravity* (µg) can be interpreted in a number of ways depending upon context. The prefix micro - (µ) is derived from the original Greek *mikros*, meaning "small." By this definition, a microgravity environment is one that will impart to an object a net acceleration small compared with that produced by Earth at its surface. In practice, such accelerations will range from about one percent of Earth's gravitational acceleration (aboard aircraft in parabolic flight) to better than one part in a million (for example, aboard Earth-orbiting free flyers).

Another common usage of micro- is found in quantitative systems of measurement, such as the metric system, where micro- means *one part in a million*. By this second definition, the acceleration imparted to an object in microgravity will be one-millionth (10^{-6}) of that measured at Earth's surface.

The use of the term microgravity in this guide will correspond to the first definition: small gravity levels or low gravity. As we describe how low-acceleration environments can be produced, you will find that the fidelity (quality) of the microgravity environment will depend on the mechanism used to create it. For illustrative purposes only, we will provide a few simple quantitative examples using the second definition. The examples attempt to provide insight into what might be expected if the local acceleration environment would be reduced by six orders of magnitude from 1g to 10^{-6}g.

If you stepped off a roof that was five meters high, it would take you just one second to reach the ground. In a microgravity environment equal to one percent of Earth's gravitational pull, the same drop would take 10 seconds. In a microgravity environment equal to one-millionth of Earth's gravitational pull, the same drop would take 1,000 seconds or about 17 minutes!

Microgravity can be created in two ways. Because gravitational pull diminishes with distance, one way to create a microgravity environment is to travel away from Earth. To reach a point where Earth's gravitational pull is reduced to one-millionth of that at the surface, you would have to travel into space a distance of 6.37 million kilometers from Earth (almost 17 times farther away than the Moon). This approach is impractical, except for automated spacecraft, since humans have yet to travel farther away from Earth than the distance to the Moon. However, a more practical microgravity environment can be created through the act of free fall.

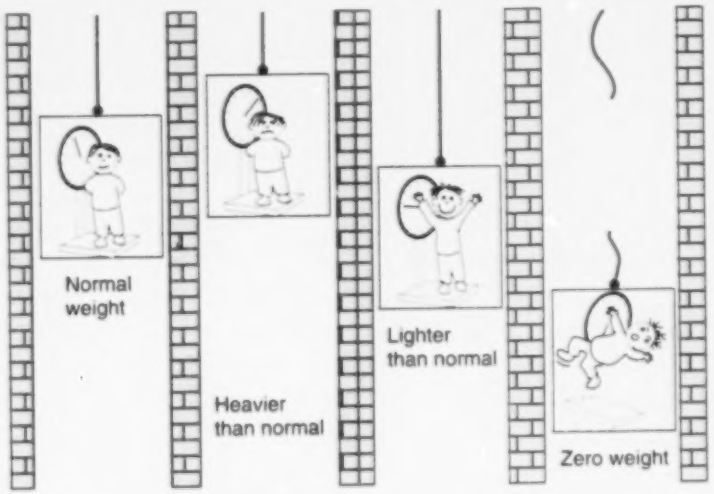


Figure 1. Acceleration and weight

The person in the stationary elevator car experiences normal weight. In the car immediately to the right, weight increases slightly because of the upward acceleration. Weight decreases slightly in the next car because of the downward acceleration. No weight is measured in the last car on the right because of free fall.

We will use a simple example to illustrate how free fall can achieve microgravity. Imagine riding in an elevator to the top floor of a very tall building. At the top, the cables supporting the car break, causing the car and you to fall to the ground. (In this example, we discount the effects of air friction on the falling car.) Since you and the elevator car are falling together, you will float inside the car. In other words, you and the elevator car are accelerating downward at the same rate. If a scale were present, your weight would not register because the scale would be falling too (Figure 1).

Gravity

Gravitational attraction is a fundamental property of matter that exists throughout the known universe. Physicists identify gravity as one of the four types of forces in the universe. The others are the strong and weak nuclear forces and the electromagnetic force.

More than 300 years ago the great English scientist Sir Isaac Newton published the important generalization that mathematically describes this universal force of gravity. Newton was the first to realize that gravity extends well beyond the domain of Earth. This realization was based on the first of three laws he had formulated to describe the motion of objects. Part of Newton's first law, the law of inertia, states that objects in motion travel in a straight line at a constant velocity unless acted upon by a net force. According to this law, the planets in space should travel in straight lines. However, as early as the time of Aristotle, the planets were known to travel on curved paths. Newton reasoned that the circular motions of the planets are the result of a net force acting upon each of them. That force, he concluded, is the same force that causes an apple to fall to the ground—gravity.

Newton's experimental research into the force of gravity resulted in his elegant mathematical statement that is known today as the **Law of Universal Gravitation**. According to Newton, every mass in the universe attracts every other mass. The attractive force between any two objects is directly proportional to the product of the two masses being measured and inversely proportional to the square of the distance separating them. If we let *F* represent this force, *r* the distance between the centers of the masses, and m_1 and m_2 the magnitude of the two masses, the relationship stated can be written symbolically as:

$$F \propto \frac{m_1 m_2}{r^2}$$

($\propto$ is defined mathematically to mean "is proportional to.") From this relationship, we can see that the greater the masses of the attracting objects, the greater the force of attraction between them. We can also see that the farther apart the objects are from each other, the less the attraction. It is important to note the inverse square relationship with respect to distance. In other words, if the distance between the objects is doubled, the attraction between them is diminished by a factor of four, and if the distance is tripled, the attraction is only one-ninth as much.

Newton's Law of Universal Gravitation was later quantified by eighteenth-century English physicist Henry Cavendish who actually measured the gravitational force between two one-kilogram masses separated by a distance of one meter. This attraction was an extremely weak force, but its determination permitted the proportional relationship of Newton's law to be converted into an equation. This measurement yielded the *universal gravitational constant* or *G*.

Deep In Space

The inverse square relationship, with respect to distance, of the Law of Gravitation can be used to determine how far to move a microgravity laboratory from Earth to achieve a 10^{-6}g environment. Distance (*r*) is measured between the centers of mass of the laboratory and of Earth. While the laboratory is still on Earth, the distance between their centers is 6,370 kilometers (equal to the approximate radius of Earth, r_e). To achieve 10^{-6}g, the laboratory has to be moved to a distance of 1,000 Earth radii. In the equation, r then becomes 1,000 r_e or r= 6.37×10^6km.

Cavendish determined that the value of *G* is 0.0000000000667 newton m^2/kg^2 or 6.67×10^{-11} Nm^2/kg^2. With G added to the equation, the Universal Law of Gravitation becomes:

$$F = G\frac{m_1 m_2}{r^2}$$

Creating Microgravity

Drop Towers and Tubes

In a practical sense, microgravity can be achieved with a number of technologies, each depending upon the act of free fall. Drop towers and drop tubes are high-tech versions of the elevator analogy presented in a previous section. The large version of these facilities is essentially a hole in the ground.

Drop towers accommodate large experiment packages, generally using a drop shield to contain the package and isolate the experiment from aerodynamic drag during free fall in the open environment.

NASA's Lewis Research Center in Cleveland, Ohio has a 145-meter drop tower facility that begins on the surface and descends into Earth like a mine shaft. The test section of the facility is 6.1 meters in diameter and 132 meters deep. Beneath the test section is a catch basin filled with polystyrene beads. The 132-meter drop creates a microgravity environment for a period of 5.2 seconds.

To begin a drop experiment, the experiment apparatus is placed in either a cylindrical or rectangular test vehicle that can carry experiment loads of up to 450 kilograms. The vehicle is suspended from a cap that encloses the upper end of the facility. Air is pumped out of the facility until a vacuum of 10^{-2} torr is achieved. (Atmospheric pressure is 760 torr.) By doing so, the acceleration effects caused by aerodynamic drag on the vehicle are reduced to less than 10^{-5} g. During the drop, cameras within the vehicle record the action and data is telemetered to recorders.

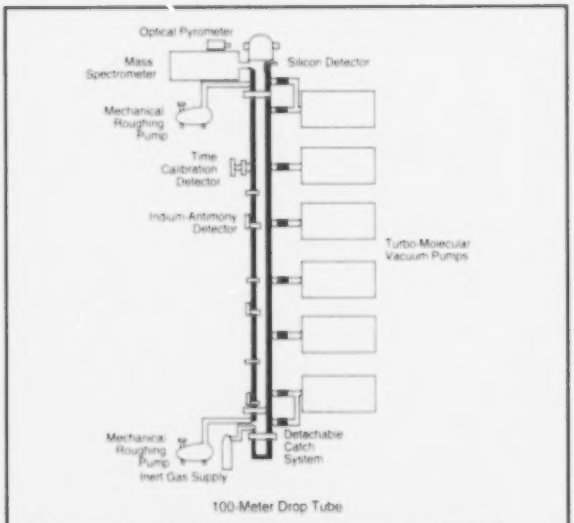


Figure 2. 100-Meter Drop Tube at the NASA Marshall Space Flight Center.

A smaller facility for microgravity research is located at the NASA Marshall Space Flight Center in Huntsville, Alabama. It is a 100-meter-high, 25.4-centimeter-diameter evacuated drop tube that can achieve microgravity for periods of as long as 4.5 seconds. The upper end of the tube is fitted with a stainless steel bell jar. For solidification experiments, an electron bombardment or an electromagnetic levitator furnace is mounted inside the jar to melt the test samples. After the sample melts, drops are formed and fall through the tube to a detachable catch fixture at the bottom of the tube (Figure 2).

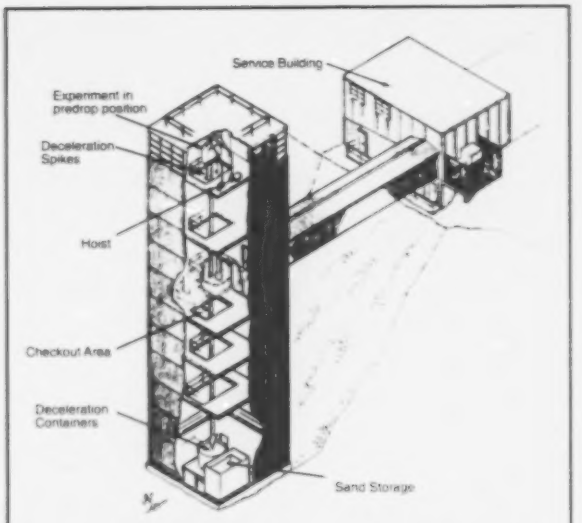


Figure 3. 30-Meter Drop Tower at the NASA Lewis Research Center.

Additional drop facilities of different sizes and for different purposes are located at the NASA Field Centers and in other countries. A 490-meter-deep vertical mine shaft in Japan has been converted to a drop facility that can achieve a 10^{-5}g environment for up to 11.7 seconds.

Aircraft

Airplanes can achieve low-gravity for periods of about 25 seconds or longer. The NASA Johnson Space Center in Houston, Texas operates a KC-135 aircraft for astronaut training and conducting experiments. The plane is a commercial-sized transport jet (Boeing 707) with most of its passenger

seats removed. The walls are padded for protection of the people inside. Although airplanes cannot achieve microgravity conditions of as high quality as those produced in drop towers and drop tubes (since they are never completely in free fall and their drag forces are quite high), they do offer an important advantage over drop facilities—experimenters can ride along with their experiments.

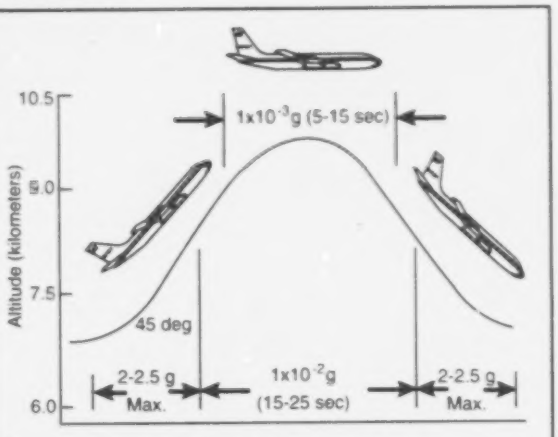


Figure 4. Parabolic Flight Characteristics.

A typical flight lasts 2 to 3 hours and carries experiments and crewmembers to a beginning altitude about 7 km above sea level. The plane climbs rapidly at a 45-degree angle (pull up), traces a parabola (push-over), and then descends at a 45-degree angle (pull out) (Figure 4). During the pull up and pull out segments, crew and experiments experience between 2g and 2.5g. During the parabola, at altitudes ranging from 7.3 to 10.4 kilometers, net acceleration drops as low as 10^{-3} g. On a typical flight, 40 parabolic trajectories are flown. The gut-wrenching sensations produced on the flight have earned the plane the nickname of "vomit comet." NASA also operates a Learjet for low-gravity research out of the NASA Lewis Research Center. Flying on a trajectory similar to the one followed by the KC-135, the Learjet provides a low-acceleration environment of $5x10^{-2}$g to $75x10^{-2}$ g for up to 20 seconds.

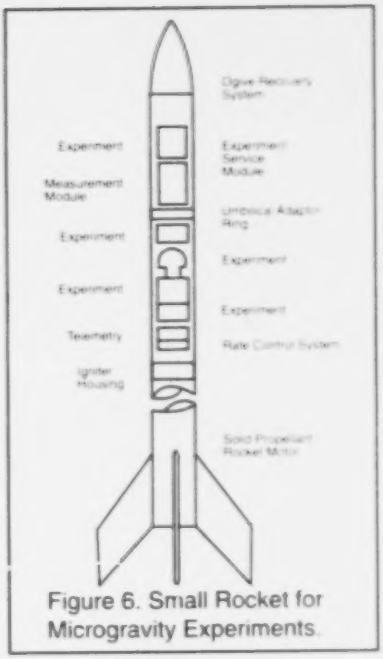


Figure 6. Small Rocket for Microgravity Experiments.

Rockets

Small rockets provide a third technology for creating microgravity. A sounding rocket follows a suborbital trajectory and can produce several minutes of free fall. The period of free fall exists during its coast, after burn out, and before entering the atmosphere. Acceleration levels are usually at or below 10^{-5}g. NASA has employed many different sounding rockets for microgravity experiments. The most comprehensive series of launches used SPAR (Space Processing Application Rocket) rockets for fluid physics, capillarity, liquid diffusion, containerless processing, and electrolysis experiments from 1975 to 1981. The SPAR could lift 300 kg payloads into free-fall parabolic trajectories lasting four to six minutes (Figures 5, 6).

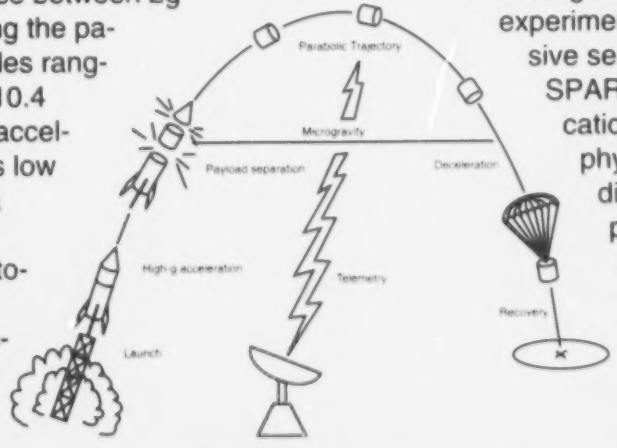


Figure 5. Rocket Parabolic Flight Profile.

Orbiting Spacecraft

Although airplanes, drop facilities, and small rockets can be used to establish a microgravity environment, all of these laboratories share a common problem. After a few seconds or minutes of low-g, Earth gets in the way and the free fall stops. In spite of this limitation, much can be learned about fluid dynamics and mixing, liquid-gas surface interactions, and crystallization and macromolecular structure. But to conduct longer term experiments (days, weeks, months, and years), it is necessary to travel into space and orbit Earth. Having more time available for experiments means that slower processes and more subtle effects can be investigated.

To see how it is possible to establish microgravity conditions for long periods of time, it is first necessary to understand what keeps a spacecraft in orbit. Ask any group of students or adults what keeps satellites and Space Shuttles in orbit and you will probably get a variety of answers. Two common answers are: "The rocket engines keep firing to hold it up." and "There is no gravity in space."

Although the first answer is theoretically possible, the path followed by the spacecraft would technically not be an orbit. Other than the altitude involved and the specific means of exerting an upward force, there would be little difference between a spacecraft with its engines constantly firing and an airplane flying around the world. In the case of the satellite, it would just not be possible to provide it with enough fuel to maintain its altitude for more than a few minutes.

The second answer is also wrong. In a previous section, we discussed that Isaac Newton proved that the circular paths of the planets through space was due to gravity's presence, not its absence.

Newton expanded on his conclusions about gravity and hypothesized how an artificial satellite could be made to orbit Earth. He envisioned a very tall mountain extending above Earth's atmosphere so that friction with the air would not be a factor. He then imagined a cannon at the top of that mountain firing cannonballs parallel to the ground. As each cannonball was fired, it was acted upon by two forces. One force, the explosion of the black powder, propelled the cannonball straight outward. If no other force were to act on the cannon ball, the shot would travel in a straight line and at a constant velocity. But Newton knew that a second force would act on the cannonball:

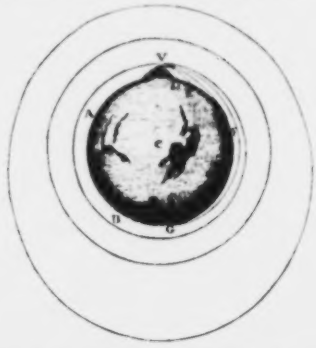


Figure 7. Illustration from Isaac Newton, *Principia, VII, Book III, p551.*

the presence of gravity would cause the path of the cannonball to bend into an arc ending at Earth's surface (Figure 7).

Newton demonstrated how additional cannonballs would travel farther from the mountain if the cannon were loaded with more black powder each time it was fired. With each shot, the path would lengthen and soon, the cannonballs would disappear over the horizon. Eventually, if a cannonball were fired with enough energy, it would fall entirely around Earth and come back to its starting point. The cannonball would begin to orbit Earth. Provided no force other than gravity interfered with the cannonball's

"Microgravity Room"

One of the common questions asked by visitors to the NASA Johnson Space Center in Houston, Texas is, "Where is the room where a button is pushed and gravity goes away so that astronauts float?" No such room exists because gravity can never be made to go away. The misconception comes from the television pictures that NASA takes of astronauts training in the KC-135 and from underwater training pictures. Astronauts scheduled to wear spacesuits for extravehicular activities train in the Weightless Environment Training Facility (WET F). The WET F is a swimming pool large enough to hold a Space Shuttle payload bay mock-up and mock-ups of satellites and experiments. Since the astronauts' spacesuits are filled with air, heavy weights are added to the suits to achieve neutral buoyancy in the water. The facility provides an excellent simulation of what it is like to work in space with two exceptions: in the pool it is possible to swim with hand and leg motions, and if a hand tool is dropped, it falls to the bottom.

motion, it would continue circling Earth in that orbit.

This is how the Space Shuttle stays in orbit. It is launched in a trajectory that arcs above Earth so that the orbiter is traveling at the right speed to keep it falling while maintaining a constant altitude above the surface. For example, if the Shuttle climbs to a 320-kilometer-high orbit, it must travel at a speed of about 27,740 kilometers per hour to achieve a stable orbit. At that speed and altitude, the Shuttle's falling path will be parallel to the curvature of Earth. Because the Space Shuttle is free-falling around Earth and upper atmospheric friction is extremely low, a microgravity environment is established.

Orbiting spacecraft provide ideal laboratories for microgravity research. As on airplanes, scientists can fly with the experiments that are on the spacecraft. Because the experiments are tended, they do not have to be fully automatic in operation. A malfunction in an experiment conducted with a drop tower or small rocket means a loss of data or complete failure. In orbiting spacecraft, crewmembers can make repairs so that there is little or no loss of data. They can also make on-orbit modifications in experiments to gather more diverse data.

Perhaps the greatest advantage of orbiting spacecraft for microgravity research is the amount of time during which microgravity conditions can be achieved. Experiments lasting for more than two weeks are possible with the Space Shuttle. When the International Space Station becomes operational, the time available for experiments will stretch to months. The International Space Station will provide a manned microgravity laboratory facility unrivaled by any on Earth (Figure 8).

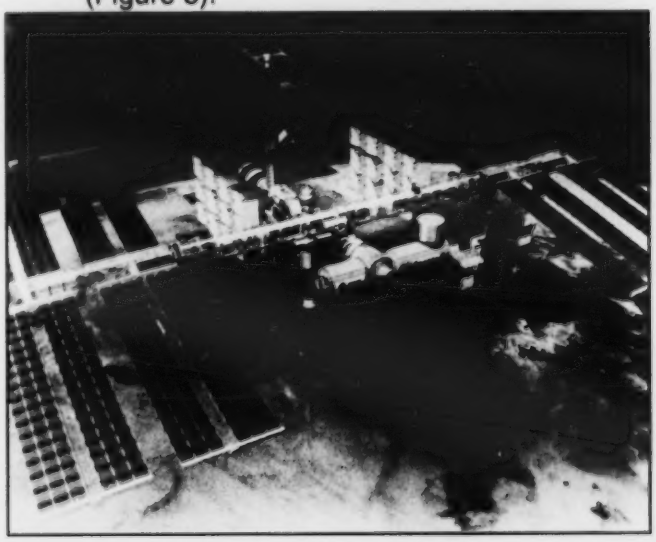


Figure 8. International Space Station.

Microgravity Primer

Gravity is a dominant factor in many chemical and physical processes on Earth.

- Heat applied to the bottom of a soup pot is conducted by the metal of the pot to the soup inside. The heated soup expands and becomes less dense than the soup above. It rises because cool, dense soup is pulled down by gravity, and the warm, less dense, soup rises to the top. A circulation pattern is produced that mixes the entire soup. This is called buoyancy-driven convection.

- Liquids of unequal density which do not interact chemically, like vinegar and oil, mix only temporarily when shaken vigorously together. Their different densities cause them to separate into two distinct layers. This is called sedimentation.

- Crystals and metal alloys contain defects and have properties which are directly and indirectly attributed to gravity-related effects. Convective flows such as those described above are present in the molten form of the material from which the solids are formed. As a result, some of the atoms and molecules making up the crystalline structure may be displaced from their intended positions. Dislocations, extra or missing half planes of atoms in the crystal structure, are one example of microscopic defects which create subtle, but important, distortions in the optical and electrical properties of the crystal.

Many basic processes are strongly influenced by gravity. For the scientific researcher, buoyancy-driven convection and sedimentation are significant phenomena because they have such a profound direct effect on the processes involved. They can also mask other phenomena that may be equally important but too subtle to be easily observed. If gravity's effects were eliminated, how would liquids of unequal densities mix? Could new alloys be formed? Could large crystals with precisely controlled crystalline and chemical perfection be grown? What would happen to the flame of a candle? There are many theories and experiments which predict the answers to these questions, but the only way to answer and fully understand these questions and a host of others is to effectively eliminate gravity as a factor. Drop towers, airplanes, sounding rockets, and the Space Shuttle make this possible, as will the International Space Station in a few years.

What are the subtle phenomena that gravity masks? What research will scientists pursue in microgravity?

The Fluid State

To most of us, the word "fluid" brings to mind images of water and other liquids. But to a scientist, the word fluid means much more. A fluid is any liquid or gaseous material that flows and, in gravity, assumes the shape of the container it is in. Gases fill the whole container; liquids on Earth fill only the lower part of the container equal to the volume of the liquid.

Scientists are interested in fluids for a variety of reasons. Fluids are an important part of life processes, from the blood in our veins and arteries to the oxygen in the air. The properties of fluids make plumbing, automobiles, and even fluorescent lighting possible. Fluid mechanics describes many processes

that occur within the human body and also explains the flow of sap through plants. The preparation of materials often involves a fluid state that ultimately has a strong impact on the characteristics of the final product.

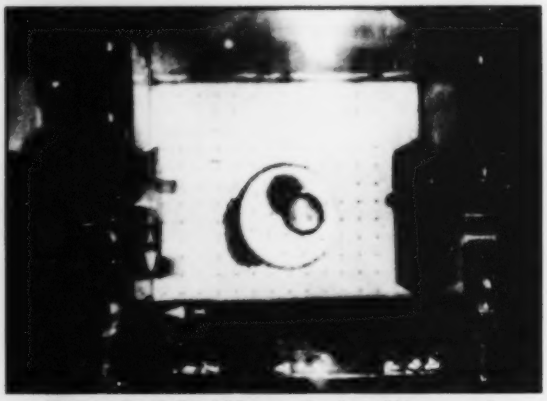


Figure 9. A liquid is manipulated by sound waves in the Drop Dynamics Module experiment on Spacelab 3. By using sound waves to position the drop, possible container wall contamination is eliminated.

Scientists gain increased insight into the properties and behavior of fluids by studying their movement or flow, the processes that occur within fluids, and the transformation between the different states of a fluid (liquid and gas) and the solid state. Studying these phenomena in microgravity allows the scientists to examine processes and conditions impossible to study when influenced by Earth's gravity. The knowledge gained can be used to improve fluid handling, materials processing, and many other areas in which fluids play a role. This knowledge can be applied not only on Earth, but also in space.

Fluid Dynamics and Transport Phenomena

Fluid dynamics and transport phenomena are central to a wide range of physical, chemical and biological processes, many of which are technologically important in both Earth- and space-based applications. In this context, the term transport phenomena refers to the different mechanisms by which energy and matter (e.g., atoms, molecules, particles, etc.) move. Gravity often introduces complexities which severely limit the fundamental understanding of a large number of these different transport mechanisms.

For example, buoyancy-driven flows, which arise from density differences in the fluid, often prevent the study of other important transport phenomena such as diffusion and surface tension-driven flows. Surface tension-driven flows are caused by differences in the temperature and/or chemical composition at the fluid surface. The fluid flows from areas where the surface tension is low to areas where it is high. Low gravity conditions can reduce by orders of magnitude the effects of buoyancy, sedimentation, and hydrostatic pressure, enabling observations and measurements which are difficult or impossible to obtain in a terrestrial laboratory. (Hydrostatic pressure is that pressure which is exerted on a portion of a column of fluid as a result of the weight of the fluid above it.)

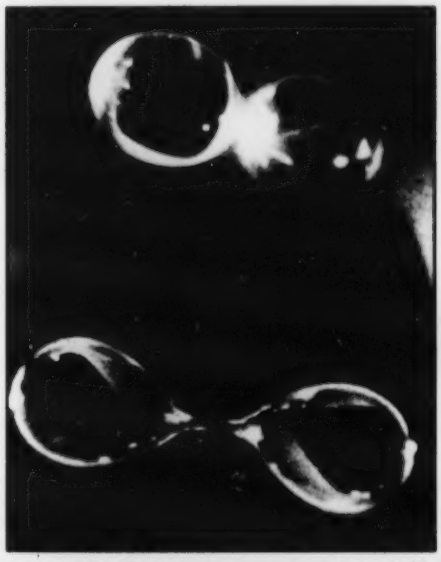


Figure 10. During an experiment on USML-1, a rotating liquid drop separates into two drops.

The systematic study of fluids under microgravity conditions holds the promise of refining existing theory or allowing the formulation of new theories to describe fluid

dynamics and transport phenomena. Such research promises to improve the understanding of those aspects of fluid dynamics and transport phenomena whose fundamental behavior is limited or affected by the influence of gravity. Several research areas contain promising opportunities for significant advancements through low-gravity experiments. These research areas include: capillary phenomena, multiphase flows and heat transfer, diffusive transport, magneto/electrohydrodynamics, colloids, and solid-fluid interface dynamics. These terms will be defined in their respective sections.

Capillary Phenomena. Capillarity describes the relative attraction of a fluid for a solid surface compared with its self-attraction. A typical example of capillary action is the rise of sap in plants. Research in capillary phenomena is a particularly fertile area for low-gravity experiments because of the increased importance of capillary forces as the effects of gravity are reduced. Such circumstances are always encountered in multiphase fluid systems where there is a liquid-liquid, liquid-vapor, or liquid-solid interface. Surface tension-driven flows also become increasingly important as the effects of gravity are reduced and can dramatically affect other phenomena such as the interactions and coalescence of drops and bubbles.

Multiphase Flow and Heat Transfer. Capillary forces also play a significant role in multiphase flow and heat transfer, particularly under reduced-gravity conditions. It is important to be able to accurately predict the rate at which heat will be transported between two-phase mixtures and solid surfaces—for example, as a liquid and gas flow through a pipe. Of course, it is equally important to be able to predict the heat exchange between the two different fluid phases. Furthermore, when the rate of transferring heat to or from the multiphase fluid system reaches a sufficient level, the liquids or gases present may change phase. That is, the liquid may boil (heat entering the liquid), the liquid may freeze (heat leaving the liquid), or the gas may condense (heat leaving the gas). While the phase change processes of melting and solidification under reduced-gravity conditions have been studied extensively—due to their importance in materials processing—similar progress has not been made in understanding the process of boiling and condensation. Although these processes are broadly affected by gravity, improvements in the fundamental understanding of such effects have been hindered by the lack of experimental data.

Diffusive Transport. Diffusion is a mechanism by which atoms and molecules move through solids, liquids, and gases. The constituent atoms and molecules spread through the medium (in this case, liquids and gases) due primarily to differences in concentration, though a difference in temperature can be an important secondary effect in microgravity. Much of the important research in this area involves studies where several types of diffusion occur simultaneously.

Figure 11. Space Shuttle *Atlantis* crewmembers John E. Blaha and Shannon W. Lucid prepare liquids in a middeck experiment on polymer membrane processing.

The significant reduction in buoyancy-driven convection that occurs in a free-fall orbit may provide more accurate measurements and insights into these complicated transport processes.

Magneto/Electrohydrodynamics. The research areas of magnetohydrodynamics and electrohydrodynamics involve the study of the effects of magnetic and electric fields on mass transport (atoms, molecules, and particles) in fluids. Low velocity fluid flows, such as those found in poor electrical conductors in a magnetic field, are particularly interesting. The most promising low-gravity research in magneto/electrohydrodynamics deals with the study of effects normally obscured by buoyancy-driven convection. Under normal gravity conditions, buoyancy-driven convection can be caused by the fluid becoming heated due to its electrical resistance as it interacts with electric and magnetic fields. The heating of a material caused by the flow of electric current through it is known as Joule heating. Studies in space may improve techniques for manipulating multiphase systems such as those containing fluid globules and separation processes such as electrophoresis, which uses applied electric fields to separate biological materials.

Colloids. Colloids are suspensions of finely divided solids or liquids in gaseous or liquid fluids. Colloidal dispersions of liquids in gases are commonly called aerosols. Smoke is an example of fine solid particles dispersed in gases. Gels are colloidal mixtures of liquids and solids where the solids have linked together to form a continuous network. Research interest in the colloids area includes the study of formation and growth phenomena during phase transitions—e.g., when liquids change to solids. Research in microgravity may allow measurement of large scale aggregation or clustering phenomena without the complication of the different sedimentation rates due to size and particle distortion caused by settling and fluid flows that occur under normal gravity.

Solid-Fluid Interface Dynamics. A better understanding of solid-fluid interface dynamics, how the boundary between a solid and a fluid acquires and maintains its shape, can contribute to improved materials processing applications. The morphological (shape) stability of an advancing solid-fluid interface is a key problem in such materials processing activities as the growth of homogeneous single crystals. Experiments in low-gravity, with significant reductions in buoyancy-driven convection, could allow mass transport in the fluid phase by diffusion only. Such conditions are particularly attractive for testing existing theories for processes and for providing unique data to advance theories for chemical systems where the interface interactions strongly depend on direction and shape.

Combustion Science

There is ample practical motivation for advancing combustion science. It plays a key role in energy transformation, air pollution, surface-based transportation, spacecraft and aircraft propulsion, global environmental heating, materials processing, and hazardous waste disposal through incineration. These and many other applications of combustion science have great importance in national economic, social, political, and military issues. While the combustion process is clearly beneficial, it is also extremely dangerous when not controlled. Enormous numbers of lives and valuable property are destroyed each year by fires and explosions. Two accidents involving U.S. spacecraft in the Apollo program were attributed to gaps in the available knowledge of combustion fundamentals under special circumstances. Planning for a permanent human

presence in space demands the development of fundamental combustion science in reduced gravity to either eliminate spacecraft fires as a practical possibility or to develop powerful strategies to detect and extinguish incipient spacecraft fires. Advances in understanding the combustion process will also benefit fire safety in aircraft, industry, and the home.

The recently developed capability to perform experiments in microgravity may prove to be a vital tool in completing our understanding of combustion processes. From a fundamental viewpoint, the most prominent feature that distinguishes combustion processes from processes involving fluid flow is the large temperature variations which invariably exist in a reacting flow. These large temperature variations are caused by highly-localized, highly-exothermic heat release from the chemical reactions characteristic of combustion processes. For example, the temperature of a reactive mixture can increase from the unreacted, ambient state of about 25°C (around room temperature) to the totally reacted state of over 2750°C. These large temperature differences lead to correspondingly large density differences and hence, to the potential existence of strong buoyancy-driven fluid flows. These flows can modify, mask, or even dominate the convective-diffusive transport processes that mix and heat the fuel and oxidant reactants before chemical reactions can be initiated. For combustion in two-phase flows, the presence of gravity introduces additional complications. Here particles and droplets can settle, causing stratification in the mixture. The effects of surface tension on the shape and motion of the surface of a large body of liquid fuel can also be modified due to the presence of buoyancy-driven flows.

Gravity can introduce a degree of asymmetry in an otherwise symmetrical phenomenon. For example, combustion of a gaseous jet injected horizontally quickly loses its symmetry along its long axis as the hot flame plume gradually tilts 'upward.' The fluid transport processes in these situations are inherently multi-dimensional and highly complex.

Important as it is, buoyancy is frequently neglected in the mathematical analysis of combustion phenomena either for mathematical simplicity or to facilitate identification of the characteristics of those controlling processes which do not depend on gravity. Such implications, however, can render direct comparison between theory and experiment either difficult or meaningless. It also weakens the feedback process between theoretical and experimental developments which is so essential in the advancement of science.

Materials Science

The current materials science program is characterized by a balance of fundamental research and applications-oriented investigations. The goal of the materials science program is to utilize the unique characteristics of the space environment to further our understanding of the processes by which materials are produced, and to further our understanding of their properties, some of which may be produced only in the space environment. The program attempts to advance the fundamental understanding of the physics associated with phase changes. This includes solidification, crystal growth, condensation from the vapor, etc. Materials science also seeks explanations for previous space-based research results for which no clear explanations exist. Research activities are supported which investigate materials processing techniques unique to the microgravity environment, or which, when studied in microgravity, may yield unique information with terrestrial applications.

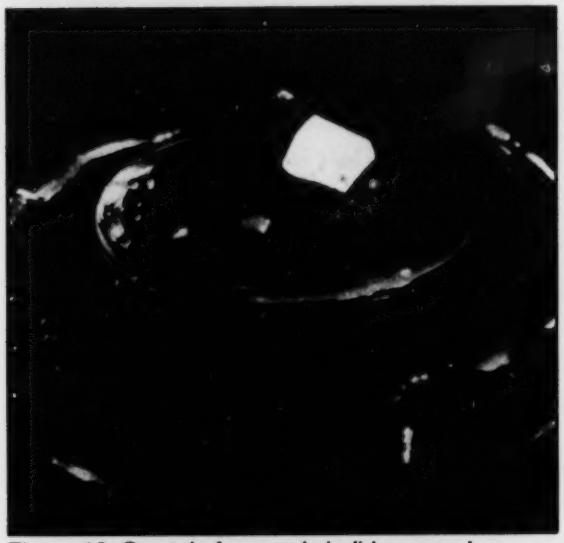


Figure 12. Crystal of mercuric iodide grown by physical vapor transport during a Spacelab experiment.

Microgravity Materials Science Background

The orbital space environment offers the researcher two unique features which are attainable on Earth to only a very limited extent. These are 'free fall' with the attendant reduced gravity environment and a high quality vacuum of vast extent. Suborbital conditions of free fall are limited to less than 10 seconds in drop towers, less than 25 seconds during aircraft maneuvers, and less than 15 minutes during rocket flights. The quality of the microgravity environment of these various ground-based options ranges from 10^{-2} g to 10^{-5} g. With the Space Shuttle, this duration has been extended to days and weeks—with Space Station and free flyers, to months and years.

In a reduced gravity environment, relative motion is slowed in direct proportion to the reduction in net acceleration. At 10^{-6} g, particles suspended in a fluid will sediment a million times more slowly than they do on Earth. Thermal and solutal convection is much less vigorous in microgravity than it is on Earth, and in some cases seems to become a secondary transport mechanism.

Both thermal and solutal convection are examples of buoyancy-driven convection. In the first case, the difference in density is caused by a difference in temperature; in the second case, the density difference is caused by the changing chemical composition of the liquid. As indicated previously, buoyancy-induced convection can be suppressed in a low-gravity environment. For many materials science investigations, this experimental condition is extremely interesting because it allows us to study purely diffusive behavior in systems for which conditions of constant density are difficult or impossible to create or for which experiments in 'convection-free' capillaries lead to ambiguous results.

To date, much of the space-based research has focused on this unique condition with respect to processing materials which are particularly susceptible to compositional nonuniformities resulting from convective or sedimentation effects. The process by which compositionally nonuniform material is produced is referred to as segregation. Some of the first microgravity experiments in metallurgy were attempts to form fine dispersions of metal particles in another metal when the two liquid metals are immiscible. Unexpected separation of the two metals seen in several low gravity experiments in this area has given us new insight into the mechanisms behind dispersion formation (fine droplets of one metal dispersed in another metal), but a complete model including the role of critical wetting, droplet migration, and particle pushing has yet to be formulated.

There is no dispute that gravity-driven convective flows in crystal growth processes affect mass transport. This has been demonstrated for crystals growing from the melt as well as from the vapor. The distribution of components in a multicomponent system has a marked influence on the resultant

properties of a material (for example, the distribution of selenium atoms in the important electronic material, GaAs). Consequently, space processing of materials has always carried with it the hope of reducing convective flows during crystal growth to such a degree that crystallization would proceed in a purely diffusive environment for mass transport, to result in crystals with uniform composition. However, the expectation of space-processed, perfectly homogeneous materials with improved properties has yet to be realized. Future experiments on crystal growth will be directed at a wide variety of electronic materials such as GaAs, triglycine sulfate, HgI_2, HgCdTe (from the vapor), CdTe, HgZnTe, $PbBr_2$ and PbSnTe. In addition, the research of our international collaborators will include InGaAs, InSb, SiAsTe, Si, GaInSb, InP, and Ge.

In order to understand crystal growth processes in microgravity, it is essential that many aspects of these phase transformations (e.g., liquid to solid, vapor to solid) be understood. This includes a thorough knowledge of the behavior of fluids (gases and liquids), a fundamental understanding of the crystallization process, and a sufficient data base of thermophysical information (e.g., thermal conductivities, diffusion coefficients, etc.) with which various theories can be tested. It may be necessary to measure some of these quantities in microgravity, as ground-based data may be either subject to error or even impossible to generate.

The flight research focussing on fundamental problems in solidification reflects this broad scope of activity, ranging from studies of morphological stability in transparent organic systems (which serve as excellent experimental models of metallic systems) to studies of metals solidifying without the confinement of a container.

Microgravity Materials Science Research

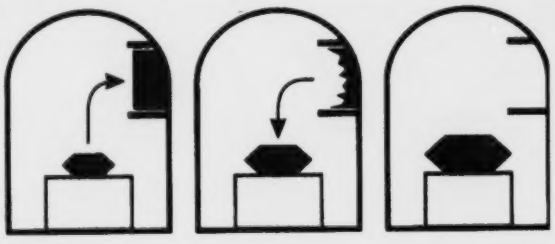
The field of materials science is extremely broad. It encompasses essentially all materials, concerns itself with the synthesis, production, and further processing of these materials, and deals with matter both on an atomistic level and on a bulk level. Although materials science addresses a myriad of problems, there are fundamental scientific issues common to all of its subdisciplines. These include evolution of the microscopic structure of the materials, transport phenomena, and the determination of relevant thermophysical properties. Interface morphology and stability, and macro- and microsegregation (the distribution of a component on the microscopic and macroscopic scales) represent ongoing challenges.

Historically, the materials science community has segmented itself on the basis of materials (composites, steels, polymers), on the basis of specific processes (casting, solidification, welding), and on the basis of fundamental physical phenomena (property measurements, diffusion studies, study of morphological stability).

Materials. The materials of interest to the microgravity materials science discipline have traditionally been categorized as electronic, metallic, glass, and ceramic. However, recent space experiments have broadened this traditional categorization to include polymeric materials as well. Additional classes of materials which may benefit greatly from being studied in a low gravity environment are: advanced composites, electronic and opto-electronic crystals, high performance metal alloys, and superconductors (high temperature and low temperature, metallic, ceramic, and organic). For their scientific and technological significance, there is also strong interest in composites, fibers, foams, and films, whatever their

constitution, when the requirement for experiments in low gravity can be clearly defined.

Processes. Because the manifestation of gravitational effects is greatest in the presence of a fluid, the following processes are of considerable importance: solidification, crystallization from solution, and condensation from the vapor. These processes have been the subject of numerous low-gravity investigations for many years. Scientifically interesting, and potentially important technologically, are the processes of welding and electrodeposition. Unique welding experiments in Skylab and recent low-gravity electrodeposition experiments in sounding rockets have produced unexplained results. The ultra-high vacuum and nearly infinite pumping rate of space offer researchers the possibility of pursuing ultra-high vacuum processing of materials and, perhaps, ultra-purification.



Seed warmed; atoms go from seed to source.

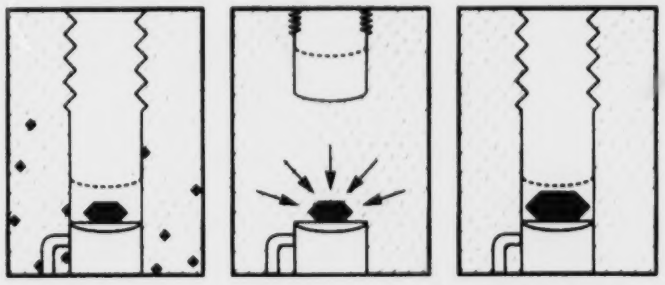
Seed cooled; crystal growth begins.

Source depleted; growth complete.

Figure 13. Vapor Crystal Growth System

Of primary importance is the utility of the space environment in helping an investigator understand the process of interest. Can a low-gravity environment be used to our advantage in elucidating important scientific information concerning these processes? Are there processes that are truly unique to the microgravity environment?

Phenomena. On a macroscale, convective motion, induced by residual accelerations or other effects, persists in the liquid or gaseous fluid from which a material is either solidifying, crystallizing, or condensing. On a microscale, the arrangement of atoms or molecules in a solid occurs at a boundary between the 'frozen' solid and the convecting fluid. The interaction between these convective flows and the resultant solid formation needs much greater understanding. A critical issue facing space-based materials science research is the response of experiments to more or less random acceleration environments within a manned spacecraft. Are compositional inhomogeneities and other major defects results of such random accelerations? What is the tolerable acceleration level for a given experiment? Are there ways of increasing experimental tolerance to a given level of acceleration? The answers to these questions will not only enhance our understanding of fundamental phenomena but also provide the foundations upon which useful space-based laboratories for materials science can be designed.



Seed crystal protected from solution; crystallites dissolving.

Crystal growth from solution initiated.

Growth completed; crystal protected.

Figure 14. Solution Crystal Growth Process

Shot Towers

The idea of using "free fall" or microgravity for research and materials processing is not a new one. American colonists used free fall to produce lead shot for their weapons. This process, patented by British merchant William Watts in 1782, involved pouring molten lead through a sieve at the top of a 15- to 30-meter-tall tower. As the lead fell, the drops became nearly perfect solid spheres that were quenched upon landing in a pool of water at the foot of the tower. Free fall produced shot superior to that produced by other methods. Scientists now explore both the phenomenon of microgravity and the use of microgravity for materials research.

Since the pioneering diffusion experiments conducted on Spacelab D-1 concerning self-diffusion in tin, there has been a heightened awareness of the need to measure the appropriate thermophysical parameters of the material under investigation. It hardly suffices, in many instances, to conduct an experiment in a diffusion-controlled environment, if the analysis of the experiment uses ground-based thermophysical data which may be in error. To avoid ambiguity in the interpretation of space experiments, it may be necessary to generate data on selected materials parameters from actual low-gravity experiments. This area of research is particularly important to the entire materials science field.

Biotechnology

The biotechnology program is comprised of three areas of research: protein crystal growth, mammalian cell culture, and fundamentals of biotechnology.

Protein Crystal Growth

The protein crystal growth program is directed to: (1) contribute to the advance in knowledge of biological molecular structures through the utilization of the space environment to help overcome a principal obstacle in the determination of molecular structures—the growth of crystals suitable for analysis by X-ray diffraction; and (2) advance the understanding of the fundamental mechanisms by which large biological molecules form crystals. The program seeks to develop these objectives through a coordinated effort of space- and ground-based research, whereby ground-based research attempts to use and explain the results of flight research, and flight research incorporates the knowledge gained from ground-based research and prior flight experience to develop refined techniques and objectives for subsequent experiments.

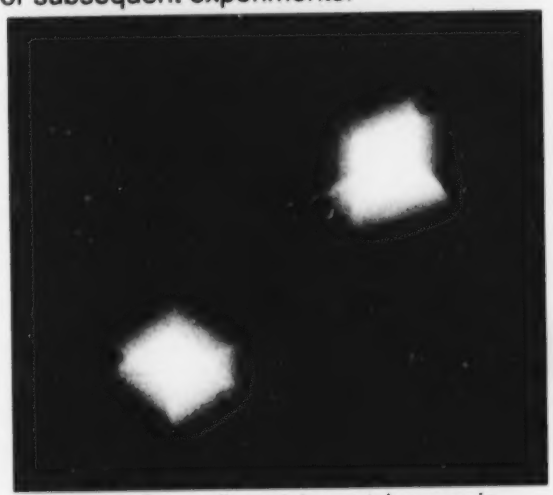


Figure 15. Canavalin protein crystals grown in microgravity.

Mammalian Cell Culture

The mammalian cell culture program seeks to develop an understanding sufficient to assess the scientific value of mammalian cells and tissues cultured under low-gravity conditions, where mechanical stresses on growing tissues and cells can be held to

very low levels. Preliminary evidence from the culture of a variety of suspended cells in rotating vessels has shown indications of increased viability and tissue differentiation. These results suggest that better control of the stresses exerted on cells or tissues can play an important role in the culture of *in vitro* tumor models, normal tissues, and other challenging problems.

Fundamentals of Biotechnology

This area of research is concerned with the identification and understanding of biotechnological processes and biophysical phenomena which can be advantageously studied in the space environment. Potential research areas include molecular and cellular aggregation, the behavior of electrically-driven flows, and capillary and surface phenomena, as applied uniquely to biological systems.

Background of Protein Crystal Growth Flight Experiments

The first protein crystal growth experiments in space were conducted on the Spacelab-1 mission in 1983 where crystals of hen egg white lysozyme and beta-galactosidase were grown. In the mid-1980's, a hand-held device for protein crystal growth experiments was developed and flown on four Shuttle missions as a precursor to the Vapor Diffusion Apparatus (VDA) - Refrigerator/ Incubator Module experiments later flown in the Shuttle middeck. Despite having encountered a number of minor technical difficulties on several flights, the project has enjoyed significant success. These include the growth of crystals to sizes and degrees of perfection beyond any ground-based efforts, and the formation of crystals in scientifically useful forms which had not been previously encountered in similar ground-based experiments. Though the physics of protein crystal growth are understood in broad terms, there is currently no agreement on a detailed mechanistic explanation for these phenomena.

Microgravity and Space Flight

Until the mid-20th century, gravity was an unavoidable aspect of research and technology. During the latter half of the century, although drop towers could be used to reduce the effects of gravity, the extremely short periods of time they provided (<6 seconds) severely restricted the type of research that could be performed.

Initial research centered around solving space flight problems created by microgravity. How do you get the proper amount of fuel to a rocket engine in space or water to an astronaut on a spacewalk? The brief periods of microgravity available in drop towers at the NASA Lewis Research Center and NASA Marshall Space Flight Center were sufficient to answer these basic questions and to develop the pressurized systems and other new technologies needed to cope with this new environment. But, they still were not sufficient to investigate the host of other questions that were raised by having gravity as an experimental variable.

The first long-term opportunities to explore the microgravity environment and conduct research relatively free of the effects of gravity came during the latter stages of NASA's first great era of discovery. The Apollo program presented scientists with the chance to test ideas for using the space environment for research in materials, fluid, and life sciences. The current NASA microgravity program had its beginning in the experiments conducted in the later flights of Apollo, the Apollo-Soyuz Test Project, and onboard Skylab, America's first space station.

Preliminary microgravity experiments conducted during the 1970's were severely constrained, either by the relatively low power levels and volume available on the Apollo spacecraft, or by the low number of flight opportunities provided by Skylab. These experiments, as simple as they were, often stimulated new insights in the roles of fluid and heat flows in materials processing. Much of our understanding of the physics underlying semiconductor crystal growth, for example, can be traced back to research initiated with Skylab.

Figure 16. Skylab.

Since the early 1980's, NASA has sent crews and payloads into orbit on board the Space Shuttle. The Space Shuttle has given microgravity scientists an opportunity to bring their experiments to low-Earth orbit on a more regular basis. The Shuttle introduced significant new capabilities for microgravity research: larger, scientifically trained crews; a major increase in payload, volume, mass, and available power; and the return to Earth of all instruments, samples, and data. The Spacelab module, developed for the Shuttle by the European Space Agency, gives scientists a laboratory with enough power and volume to conduct a limited range of sophisticated microgravity experiments in space.

Use of the Shuttle for microgravity research began in 1982, on its third flight, and continues today on many missions. In fact, most Shuttle missions carry microgravity experiments as secondary payloads.

Spacelab-1, November 1983

The Spacelab-1 mission was launched in November 1983. Over ten days, the seven crewmembers carried out a broad variety of space science experiments, including research in microgravity sciences, astrophysics, space plasma physics, and Earth observations.

Although the primary purpose of the mission was to test the operations of the complex Spacelab and its subsystems, the 71 microgravity experiments, conducted using instruments from the European Space Agency, produced many interesting and provocative results. One investigator used the travelling heater method to grow a crystal of gallium antimonide doped with tellurium (a compound useful for making electronic devices). Due to the absence of gravity-driven convection, the space-grown crystal had a far more uniform distribution of tellurium than could be achieved on Earth. A second investigator used molten tin to study diffusion in low gravity—research that can improve our understanding of the behavior of molten metals. A German investigator grew protein crystals that were significantly better than those grown from the same starting materials on the ground. These crystals were analyzed using X-rays to determine the structure of the protein that was grown.

Spacelab-3, April 1985

Another Shuttle mission using the Spacelab module was Spacelab-3, which flew in April 1985. SL-3 was the first mission to include U.S.-developed microgravity research instruments in the Spacelab. One of these instruments supported an experiment to study the growth of crystals of mercury iodide—a material of significant interest for use as a sensitive detector of X-rays and gamma rays. The experiment produced a crystal of mercury iodide grown at a rate much higher than that achievable on the ground. Despite the high rate of growth and relatively short growth time available, the resulting crystal was as good as the best crystal grown in the Earth-based laboratory. Another U.S. experiment consisted of a series of tests on fluid behavior using a spherical test cell. The microgravity environment allowed the researcher to use the test cell to mimic the behavior of the atmosphere over a large part of Earth's surface. Results from this experiment have been used to improve numerical models of our atmosphere.

Spacelab D-1, October 1985

In October 1985, six months after the flight of SL-3, NASA launched a Spacelab mission sponsored by the Federal Republic of Germany, designated Spacelab-D1. This mission included a significant number of sophisticated microgravity materials and fluid science experiments. American and German scientists conducted experiments to synthesize high quality semiconductor crystals useful in infrared detectors and lasers. These crystals had improved properties and were more uniform in composition than their Earth-grown counterparts. Researchers also successfully measured critical properties of molten alloys. On Earth, convection-induced disturbances make such measurements impossible.

Spacelab Life Sciences-1, June 1991

The Spacelab Life Sciences-1 mission, flown in June 1991, was the first Spacelab mission dedicated to life sciences research. Mission experiments were aimed at trying to answer many important questions regarding the functioning of the human body in microgravity and its readaptation to the normal environment on Earth. Ten major investigations probed autonomic cardiovascular controls, cardiovascular adaptation to microgravity, vestibular functions, pulmonary function, protein metabolism, mineral loss, and fluid-electrolyte regulation.

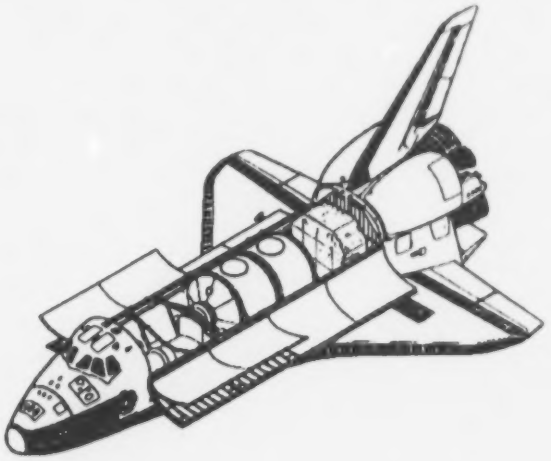


Figure 17. Spacelab long module in Orbiter payload bay.

International Microgravity Laboratory-1, January 1992

More than 220 scientists from the United States and 14 other countries contributed to the experiments flown on the first International Microgravity Laboratory (IML-1) in January 1992. Since IML-1 researchers have reported impressive results for mission experiments. Several biotechnology experiments concerned with protein crystal growth enabled NASA scientists to successfully test and compare two different crystal-growing devices. For example, U.S. researchers used a Protein Crystal Growth apparatus to obtain unusually high quality crystals of

human serum albumin (HSA), which is the most abundant protein in human blood. Because the space crystals were of much better quality than had been obtained on Earth, it has since been possible to use X-ray methods to determine important details of atom positions within the crystal structure. This work may have major medical applications, especially in the development of methods for attaching therapeutic drugs to HSA, which could then transport a drug in the bloodstream to body sites where it is needed.

A German device called the Cryostat also produced superior-quality crystals of proteins from several microorganisms. One experiment yielded unusually large crystals of the satellite tobacco mosaic virus (STMV), which has roles in diseases affecting more than 150 crop plants. Using the large crystals, researchers were then able to decipher the overall structure of STMV's genetic material, which is located deep within the tiny virus. Principal Investigator Dr. Alexander McPherson reported that the STMV space crystals produced "the best resolution data obtained on any virus crystal, by any method, anywhere." As a result, scientists now have a much clearer understanding of the overall structure of STMV. This information is useful in efforts to develop strategies for combating viral damage to crops.

IML-1 also carried experiments designed to probe how microgravity affects the internal structure of metal alloys as they solidify. When an alloy solidifies, tiny crystal branches called "dendrites" form in the cooling liquid. On Earth, gravity-driven fluid flow (convection) in the liquid influences forming dendrites. Among other effects, convection can produce flaws that undermine key properties of the alloy, such as its mechanical strength and ability to resist corrosion. However, by processing alloys in a low gravity environment, it may be possible to understand the role gravity plays in determining alloy properties. In the Casting and Solidification Technology (CAST) experiment, a simple alloy was solidified under controlled conditions. Investigators are still interpreting data from the tests, but preliminary results indicate that the alloy solidified about 50 percent faster than on Earth, and far fewer structural flaws developed. These growth characteristics matched the predictions of existing models, providing experimental evidence that current hypotheses about alloy formation are correct.

United States Microgravity Laboratory - 1, June 1992

In June 1992 the first United States Microgravity Laboratory (USML-1) flew aboard a 14-day shuttle mission, the longest up to that time. This Spacelab-based mission was an important step in a long-term commitment to build a microgravity program involving government, academic, and industrial researchers. This mission marked the beginning of a new era in microgravity research.

The payload included 31 experiments in biotechnology, combustion science, fluid physics, materials science, and technology demonstrations. Several investigations used facilities or instruments from previous flights, including the Protein Crystal Growth (PCG) facility, a Space Acceleration Measurement System (SAMS), and the Solid Surface Combustion Experiment (SSCE). New experiment facilities, all designed to be reusable on future missions, included: the Crystal Growth Furnace, a Glovebox provided by the European Space Agency, the Surface Tension Driven Convection Experiment apparatus (STDCE), and the Drop Physics Module. The mission was an unqualified operational success in all of the areas listed above, with the crew conducting

what became known as a "dress rehearsal" for the International Space Station.

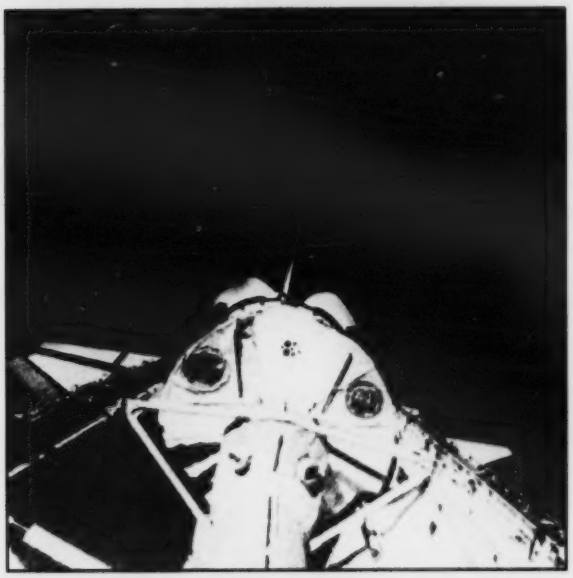


Figure 18. The first Spacelab mission dedicated to United States microgravity science on USML-1. The coast of Florida appears in the background.

USML-1 included the first use in space of the Crystal Growth Furnace (CGF), a device that permitted investigators to grow crystals of four different semiconductor materials at temperatures as high as 1260°C. One space-grown CdZnTe crystal developed far fewer imperfections than even the best Earth-grown crystals, results that far exceeded pre-flight expectations. Thin crystals of HgCdTe grown from the vapor phase had mirror-smooth surfaces even at high magnifications. This type of surface was not observed on Earth-grown crystals. Semiconductors (The most widely used one is silicon.) are used in computer chips and other electronics.

Other USML-1 experiments also contributed to NASA's protein crystal growth program. Sixteen different investigations run by NASA researchers used the Glovebox (GBX), which provided a safe enclosed working area; it also was equipped with photographic equipment to provide a visual record of investigation operations. The GBX allowed crew members to perform protein crystallization studies as they would on Earth, including procedures that require hands-on manipulation. Among other results, use of the GBX provided the best-ever crystals of malic enzyme that may be useful in developing anti-parasitic drugs.

Researchers used the STDCE apparatus to explore how internal movements of a liquid are created when there are spatial differences in temperature on the liquid's surface. The results are in close agreement with advanced theories and models that the experiment researchers developed.

In the Drop Physics Module, sound waves were used to position and manipulate liquid droplets. Surface tension controlled the shape of the droplets in ways that confirmed theoretical predictions. Preliminary results indicate that the dynamics of rotating drops of silicone oil also conformed to theoretical predictions. Results of this kind are significant in that they illustrate an important part of the scientific method: hypotheses are formed, and experiments are conducted to test them.

The burning of small candles in the Glovebox provided new insights into how flames can exist in an environment in which there is no air flow. Astronauts burned small candles in the Glovebox, an enclosed, safe environment. The results were similar (though much longer lived) to what can be seen by conducting the experiment in free fall, here on Earth. (See *Activity 8, Candle Drop*, in the Activities section of this teacher's guide.) The candles burned for about 45-60 seconds in the microgravity of continuous free fall aboard the Space Shuttle *Columbia*.

Another GBX investigation tested how wire insulation burns under different conditions, including in perfectly still air (no air flow) and in air flowing through the chamber from different directions. This research has yielded extremely important theoretical information. It also has practical applications, including methods for further increasing fire safety aboard spacecraft.

The crew of scientist astronauts in the spacelab played an important role in maximizing the science return from this mission. For instance, they attached a flexible type of glovebox, which provided an extra level of safety, to the Crystal Growth Furnace. The furnace was then opened, previously processed samples were removed and an additional sample was inserted. This enabled another three experiments to be conducted. (Two other unprocessed samples were already in the furnace.)

Spacelab-J, September, 1992

The Spacelab-J (SL-J) mission flew in September 1992. SL-J was the first space shuttle mission shared by NASA and Japan's National Space Development Agency (NASDA). It also was the most ambitious scientific venture between the two countries to date.
NASA microgravity experiments focused on protein crystal growth and evaluating the SAMS (Space Acceleration Measurement System) that flew on IML-1.

NASDA's science payload consisted of 22 experiments focused on materials science and the behavior of fluids, and 12 human biology experiments. Researchers are currently analyzing data from these investigations. NASDA also contributed two devices that could be used on future missions. One of these, the Large Isothermal Furnace, is used to explore how various aspects of processing affect the structure and

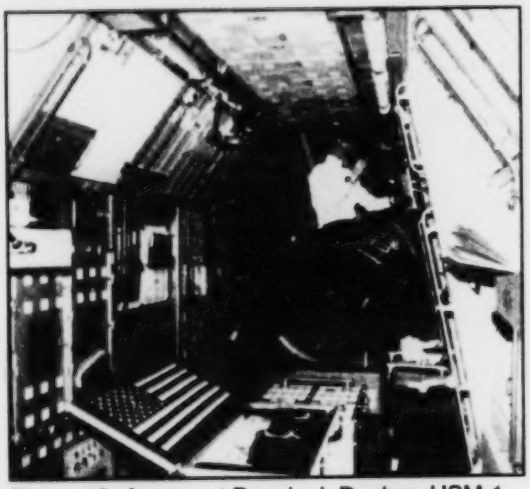


Figure 19. Astronaut Bonnie J. Dunbar, USM-1 payload commander, is about to load a sample in the Crystal Growth Furnace as payload specialist Lawrence J. DeLucas, at the multipurpose glovebox, confers with her.

properties of materials. The second apparatus was a Free-Flow Electrophoresis Unit, which can be used to separate different types of molecules in a fluid. In microgravity, the unit may produce purer samples of certain substances than can be obtained on Earth.

United States Microgravity Payload-1, October, 1992

The first United States Microgravity Payload (USMP-1) flew on a 10-day Space Shuttle mission launched on October 22, 1992. The mission was the first in an ongoing effort that employs "telescience" to conduct experiments on a carrier in the Space Shuttle Cargo Bay. Telescience refers to microgravity experiments that scientists on the ground can supervise by remote control.

The carrier in the Cargo Bay consisted of two Mission Peculiar Equipment Support Structures (MPESS). The on-board Space Acceleration Measurement System (SAMS) measured how crew movements, equipment operation, and thruster firings affected

the microgravity environment during the experiments. This information was relayed to scientists on the ground, who then correlated it with incoming experiment data.

A high point of USMP-1 was the beginning of MEPHISTO, a multi-mission collaboration between NASA scientists and French researchers. MEPHISTO is designed to study changes in molten metals and some other substances as they solidify. Three identical samples of one alloy (a combination of tin and bismuth) were solidified, melted, and resolidified more than 40 times, under slightly different conditions each time. As each cycle ended, data was transmitted from the Space Shuttle to NASA's Marshall Space Flight Center in Huntsville, Alabama. There, researchers analyzed the information and sent back commands for adjustments. In all, the investigators relayed more than 5000 commands directly to their instruments on orbit. Researchers are comparing mission data with the predictions of theoretical models. Conducting the experiments in microgravity enabled the researchers to obtain conditions during solidification that more closely agree with those assumed by the models. On Earth, gravity effects skew the conditions that develop during solidification. This first MEPHISTO effort proved that telescience projects can be carried out efficiently, with successful results.

A lambda point is the combination of temperature and pressure at which a normal liquid changes to a superfluid. On Earth, effects of gravity make it impossible to measure properties of substances very close to this point. On USMP-1, a Lambda Point Experiment took advantage of reduced gravity in Earth orbit. As liquid helium was cooled to an extremely low temperature—a little more than 2°K above absolute zero—investigators measured changes in its properties immediately before it changed from a normal fluid to a superfluid. Performing the test in microgravity yielded temperature measurements accurate to within a fraction of one billionth of a degree—several hundred times more accurate than would have been possible in normal gravity. Overall the new data was five times more accurate than in any previous experiment.

United States Microgravity Payload-2, March, 1994

The second United States Microgravity Payload (USMP-2) flew aboard the Space Shuttle Columbia for 14 days from March 4 to March 18, 1994. Building on the success of telescience in USMP-1, the Shuttle Cargo Bay carried four primary experiments which were controlled by approximately

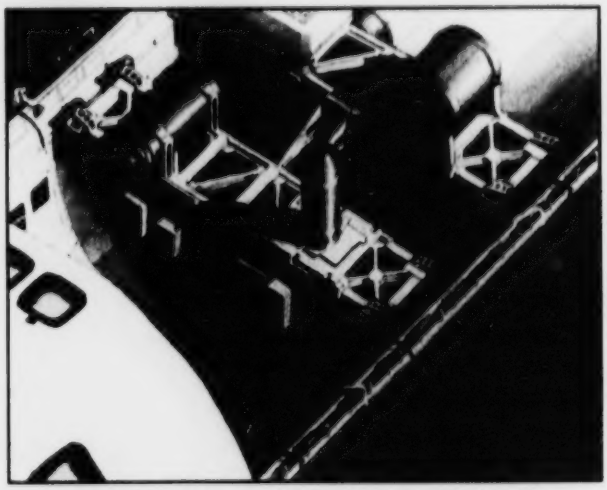


Figure 20. USMP-2 experiments mounted in the forward section of the open payload bay of the Space Shuttle.

10,000 commands relayed by scientists at NASA Marshall Space Flight Center. USMP-2 also included two Space Acceleration Measurement Systems (SAMS), which provided scientists on the ground with nearly instant feedback on how various kinds of motion—including crew exercise and vibrations from thruster engines—affected mission experiments. An Orbital

Acceleration Research Experiment (OARE) in the Cargo Bay collected additional data on acceleration and served as a test run for a United States Microgravity Laboratory mission currently slated for September, 1995.

Throughout the mission, the Critical Fluid Light Scattering Experiment (CFLSE)—nicknamed "Zeno"—analyzed the behavior of the element xenon as it fluctuated between two different states, liquid and gas. First, a chamber containing liquid xenon was heated. Then, laser beams were passed through the chamber as the xenon reached temperatures near this transition point, and a series of measurements were taken of how the laser beams were deflected (scattered) as the xenon shifted from one state to another. Researchers expected that performing the experiment on orbit would provide more detailed information about how a substance changes phase than could be obtained on Earth. In fact, the results produced observations more than 100 times more precise than the best measurement on the ground.

An Isothermal Dendritic Growth Experiment (IDGE) examined the solidification of a material that is a well-established model for metals. This material is especially useful as a model because it is transparent, so that a camera can actually record what happens inside a sample as it freezes. In 59 experiments conducted during 9 days, over 100 television images of growing dendrites (branching structures that develop as a molten metal solidifies) were sent to the ground and examined by the research team. In another successful demonstration of telescience, the team relayed back more than 100 commands to the IDGE, fine-tuning its operations. Initial findings have already identified a major role gravity that plays as a metal changes from a liquid to a solid on Earth. Space Acceleration Measurement System data obtained during IDGE operations provided insight on how small accelerations during space experiments can influence the processes.

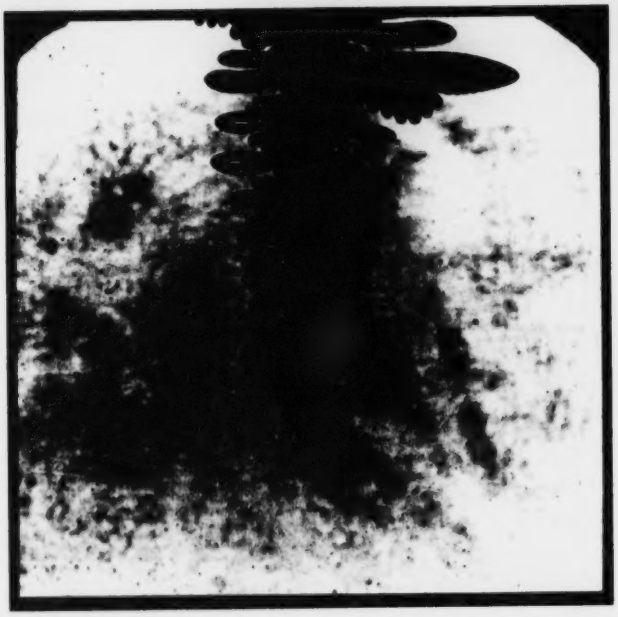


Figure 21. A dendrite grown in the Isothermal Dendritic Growth Experiment (IDGE) aboard the USMP-2. This is an example of how most metals solidify.

USMP-2 also included a second MEPHISTO experiment, following up the first in this joint U.S./French effort that was part of USMP-1. On this mission, the MEPHISTO apparatus was used for U.S. experiments to test how gravity affects the formation of crystals in an alloy that behaves much like a semiconductor during crystal growth. Another USMP-2 experiment, using the Advanced Automated Directional Solidification Furnace (AADSF), will also help shed new light on how such crystals grow. A 10-day experiment using the AADSF yielded a large, well-controlled sample of an alloy semiconductor. As this sample is analyzed, researchers should be able to verify or refute theories related to how such crystals form. That information in

turn may eventually be used to produce improved semiconductors here on the ground.

International Microgravity Laboratory-2, July 1994

The second International Microgravity Laboratory (IML-2), with a payload of 82 major experiments, flew in July 1994 on the longest Space Shuttle flight to date. IML-2 truly was a world class venture, representing the work of scientists from the U.S. and 12 other countries. The mission recorded an impressive list of "firsts." Experiments from NASA's Microgravity Science and Applications Program included investigations in materials science, biotechnology, and fluid physics.

Materials science experiments focused on various types of metal processing. One was sintering, a process that can combine different metals by applying heat and pressure to them. A series of three sintering experiments expanded the use in space of the Large Isothermal Furnace first flown on the SL-J mission in 1992. It successfully sintered alloys of nickel, iron, and tungsten.

Other experiments explored the capabilities of a German-built facility called TEMPUS. Designed to position experiment samples away from the surfaces of a container, in theory TEMPUS could eliminate processing side effects of containers. Experiments of four U.S. scientists were successfully completed, and the research team developed improved procedures for managing multi-user facilities.

Biotechnology experiments expanded research use of the Advanced Protein Crystallization Facility, developed by the European Space Agency. The facility's 48 growth chambers operated unattended throughout the flight, producing high-quality crystals of 9 proteins. High-resolution video cameras monitored critical crystal growth experiments, providing the research team with a visual record of the processes. U.S. investigators used the Bubble, Drop, and Particle Unit to study how changing temperature influences the movement and shape of gas bubbles and liquid drops. A newly developed Critical Point Facility worked flawlessly. This device enables a researcher to study how a fluid behaves at its critical point. This point occurs at the highest temperature where liquid and vapor phases can coexist. Research using the Critical Point Facility will be applicable to a broad range of scientific questions, including how various characteristics of solids change under different experimental conditions.

Secondary Objectives

In addition to Spacelab flights, NASA frequently flies microgravity experiments in the Space Shuttle middeck, in the cargo bay, and in the Get-Away-Special (GAS) canisters. Since 1988, NASA has built on the results of the first Spacelab mission by growing crystals of many different kinds of proteins on the Shuttle middeck, including several sets of space-grown protein crystals that are substantially better than Earth-grown crystals of the same materials. Medical and agricultural researchers hope to use information from these protein crystals to improve their understanding of how the proteins function.

Research conducted in the Shuttle middeck has also led to the first space product: tiny spheres of latex that are significantly more uniform in size than those produced on the ground. These precision latex spheres are so uniform that they are sold by the National Institute of Standards and Technology (NIST) as a reference standard for calibrating devices such as electron microscopes and particle counters.

Activities

A Note on Measurement:
These activities use metric units of measure. In a few exceptions, notably within the "materials needed" lists, English units have been listed. In the United States, metric-sized parts, such as screws, wood stock, and pipe are not as accessible as their English equivalents. Therefore, English units have been used to facilitate obtaining required materials.

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Activity 1

Around The World

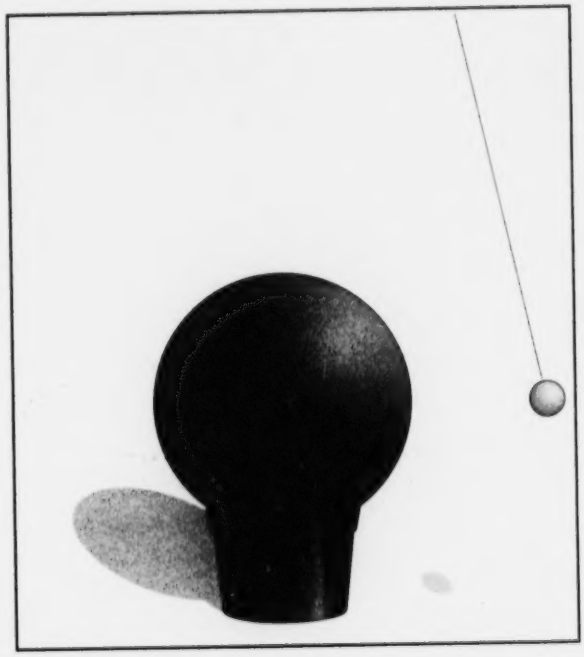
OBJECTIVE:

To model how satellites orbit Earth.

BACKGROUND:

The manner in which satellites orbit Earth is often explained as a balance that is achieved when the outward-pulling centrifugal force of a revolving object is equal to the inward pull of gravity. However, if we examine Isaac Newton's First Law of Motion, we can see why this explanation is incomplete. According to this law, objects in motion remain in motion in a straight line unless acted upon by an unbalanced force. Because Earth-orbiting objects follow elliptical paths around Earth and not a straight line, forces cannot, by definition, be balanced. Force is directional. It is a push or a pull in a particular direction. At any one moment, the force of gravity on a satellite is exerted in the direction of a line connecting the center of mass of Earth to the center of mass of the satellite. Because the satellite is not stationary, the direction of this line, and consequently the direction of the force, is constantly changing. This is the unbalanced force that curves the path of the satellite.

A second problem with the satellite orbit explanation is that centrifugal force is not an actual force but an effect. The difference is important. For example, if you are a passenger riding in a car that makes a sharp turn to the left, you feel yourself



pushed against the right side door. This is interpreted as an outward directed force but is it really an outward directed force? What would happen to you if the door were to open suddenly? Rather than try to answer these questions in an automobile, a simple demonstration can be done. Attach a ball to a string and twirl the ball in a circle as you hold the other end of the string. The ball travels on a path similar to a satellite orbit. Feel the outward pulling force as you twirl the ball. Next, release the ball and observe where it goes. If that force you experienced were really outward, the ball would fly straight away from you. Instead, the ball travels on a tangent to the circle.

What is actually happening is that the ball is attempting to travel in a straight line due to its inertia. The string, acts as an unbalanced force that changes the ball's

path from a straight line to a circle. The outward pull you feel is really the ball's resistance to a change in direction. Through the string, you are forcing the ball from a straight path to a circle. In the case of the automobile example, if the door were to pop open during a turn, you would fall out of the car and continue moving in the same direction the car was moving at the moment the door opened. While you perceive your motion as outward, the automobile is actually turning away from you as you go in a straight line.

In this demonstration, a simple model of a satellite orbiting Earth is created from a large stationary ball and a smaller ball at the end of a string. The ball and string become a pendulum that tries to swing toward the middle of the globe. However, the ball travels in an orbit around the globe when it is given a horizontal velocity in the correct direction. Although the small ball attempts to fall to the center of the larger ball, its falling path becomes circular because of its horizontal velocity.

MATERIALS NEEDED:

Large ball
Small ball
2 meters of string
Flower pot

PROCEDURE:

Step 1. Attach the 2 meter long string to the smaller ball (satellite). This can be done by drilling or poking a hole through the ball, threading it through to the other side, and knotting the string.

Step 2. Place the large ball (Earth) on the flower pot in the center of an open space.

Step 3. Select one student to stand above Earth and hold the satellite by the end of the string attached to it. This student's hand should be directly over the "north pole" of Earth and the satellite ball should rest against the side of Earth at its "equator."

Step 4. Select a second student to launch the satellite. Try pushing the satellite straight out from Earth. Try launching the satellite in other directions.

QUESTIONS:

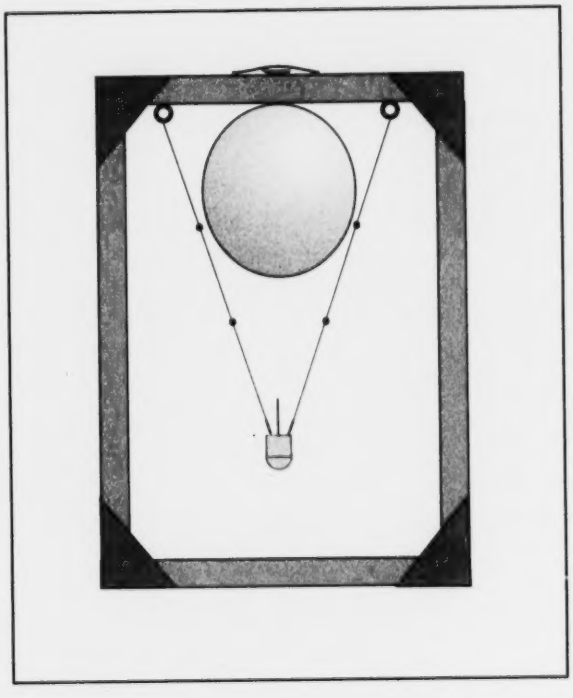
1. What path does the satellite follow when it is launched straight out from Earth?
2. What path does the satellite follow when it is launched at different angles from Earth's surface?
3. What affect is there from launching the satellite at different speeds?
4. Is it correct to say that a satellite is in a continual state of free-fall? Why doesn't the satellite strike Earth?
5. What causes a satellite to return to Earth?

FOR FURTHER RESEARCH:

1. Investigate the mathematical equations that govern satellite orbits such as the relationship between orbital velocity and orbital radius.
2. Learn about different kinds of satellite orbits (e.g., polar, geostationary, geosynchronous, etc.) and what they are used for.

Activity 2

Free Fall Demonstrator



OBJECTIVE:

To demonstrate that free fall eliminates the local effects of gravity.

BACKGROUND:

Microgravity conditions can be created in a number of ways. Amusement park customers feel a second or two of low-gravity on certain high-performance rides. Springboard divers experience low-gravity from the moment they leave the board until they hit the water. NASA achieves several seconds of microgravity with drop towers and drop tubes. Longer periods, from 25 seconds to a minute, can be achieved in airplanes following parabolic trajectories. Microgravity conditions lasting several minutes are possible using unmanned sounding rockets. However, the longest periods of microgravity are achieved with orbiting spacecraft.

The free fall demonstrator in this activity is an ideal device for classroom demonstrations on the effect of low-gravity. When stationary, the lead fishing weight stretches the rubber band so that the weight hangs near the bottom of the frame. When the frame is dropped, the whole apparatus goes into free fall, so the weight (the force of gravity) of the sinker becomes nearly zero. The stretched rubber bands then have no force to counteract their tension, so they pull the sinker, with the pin, up toward the balloon, causing it to pop. (In fact, initially the sinker's acceleration toward the balloon will be at 9.8 m/s^2. Before the frame was dropped, tension in the rubber bands compensated for gravity on the sinker, so the force from that tension will accelerate the sinker at the same rate that gravity would.) If a second frame, with string instead of rubber bands supporting the weight, is used for comparison, the pin will not puncture the balloon as the device falls.

The demonstration works best when students are asked to predict what will happen when the frame is dropped. Will the balloon pop? If so, when will it pop? If your school has videotape equipment, you may wish to videotape the demonstration and use the slow motion controls on the playback machine to determine more precisely when the balloon popped.

MATERIALS NEEDED:

2 pieces of wood 16x2x1 in.
2 pieces of wood 10x2x1 in.
4 wood screws (#8 or #10 by 2 in.)
8 corner brace triangles from 1/4" plywood
Masking Tape
Glue
2 screw eyes
4-6 rubber bands
1 6-oz fishing sinker or several lighter sinkers taped together
Long sewing pin or needle
Small round balloons
Short piece of string
Drill, 1/2 in. bit, and bit for piloting holes for wood screws
Screwdriver
Pillow or chair cushion
(Optional - Make a second frame with string supporting the sinker.)

PROCEDURE:

Step 1. Assemble the rectangular supporting frame as shown in the diagram. Be sure to drill pilot holes for the screws and glue the frame pieces before screwing them together. Brace the front and back of each corner with small triangles of plywood. Glue and nail them in place.

Step 2. Drill a 1/2 inch-diameter hole through the center of the top of the frame. Be sure the hole is free of splinters.

Step 3. Screw the two screw eyes into the underside of the top of the frame as shown in the diagram. (Before doing so, check to see that the metal gap at the eye is wide enough to slip a rubber band over it. If not, use pliers to spread the gap slightly.)

Step 4. Loop three rubber bands together and then loop one end through the metal loop of the fishing sinker(s).

Step 5. Follow the same procedure with the other three rubber bands. The fishing weight should hang downward like a swing, near the bottom of the frame. If the weight hangs near the top, the rubber bands are too strong. Replace them with thinner rubber bands.

Step 6. Attach the pin or needle, with the point upward. There are several ways of doing this depending upon the design of the weight. If the weight has a loop for attaching it to fishing line, hold the pin or needle next to the loop with tape. It may be possible to slip it through the rubber band loops to hold it in place. Another way of attaching the pin or needle is to drill a small hole on the top of the weight to hold the pin or needle.

Step 7. Inflate the balloon, and tie off the nozzle with a short length of string. Thread the string through the hole and pull the balloon nozzle through. Pull the string snugly and use a piece of tape to hold it.

Step 8. Ask the students to predict what will happen when the entire frame is dropped.

Step 9. Place a pillow or cushion on the floor. Raise the demonstrator at least 2 meters off the floor. Do not permit the weight to swing. Drop the entire unit onto the cushion. The balloon will pop almost immediately after release.

Activity 3

Falling Water

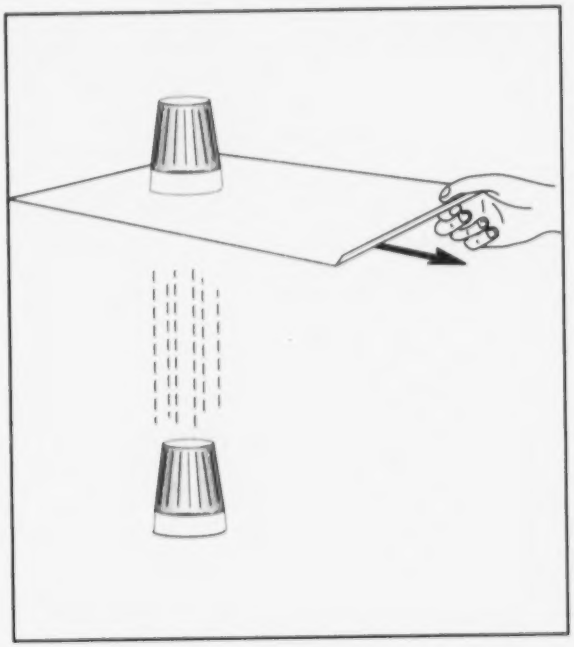
OBJECTIVE:

To demonstrate that free fall eliminates the local effects of gravity.

BACKGROUND:

Weight is a property that is produced by gravitational force. An object at rest on Earth will weigh only one-sixth as much on the Moon because of the lower gravitational force there. That same object will weigh almost three times as much on Jupiter because of the giant planet's greater gravitational attraction. The apparent weight of the object can also change on Earth simply by changing its acceleration. If the object is placed on a fast elevator accelerating upward, its apparent weight would increase. However, if that same elevator were accelerating downward, the object's apparent weight would decrease. Finally, if that elevator were accelerating downward at the same rate as a freely falling object, the object's apparent weight would diminish to near zero.

Free fall is the way scientists create microgravity for their research. Various techniques, including drop towers, airplanes, sounding rockets, and orbiting spacecraft, achieve different degrees of perfection in matching the actual acceleration of a free-falling object.



In this demonstration, a water-filled cup is inverted and dropped. Before release, the forces on the cup and water (their weight, caused by Earth's gravity) are counteracted by the cookie sheet. On release, if no horizontal forces are exerted on the cup when the sheet is removed, the only forces acting (neglecting air) are those of gravity. Since Galileo demonstrated that all objects accelerate similarly in Earth's gravity, the cup and water move together. Consequently, the water remains in the cup throughout the entire fall.

To make this demonstration possible, two additional scientific principles are involved. The cup is first filled with water. A cookie sheet is placed over the cup's mouth, and the sheet and the cup are

MATERIALS NEEDED:
Plastic drinking cup
Cookie sheet (with at least one edge without a rim)
Soda pop can (empty)
Sharp nail
Catch basin (large pail, waste basket)
Water
Chair or step-ladder (optional)
Towels

inverted together. Air pressure and surface tension forces keep the water from seeping out of the cup. Next, the cookie sheet is pulled away quickly, like the old trick of removing a table cloth from under a set of dishes. The inertia of the cup and water resists the movement of the cookie sheet so that both are momentarily suspended in air. The inverted cup and the water inside fall together.

PROCEDURE:

Step 1. Place the catch basin in the center of an open area in the classroom.
Step 2. Fill the cup with water.
Step 3. Place the cookie sheet over the opening of the cup. Hold the cup tight to the cookie sheet while inverting the sheet and cup.
Step 4. Hold the cookie sheet and cup high above the catch basin. You may wish to stand on a sturdy table or climb on a step-ladder to raise the cup higher.
Step 5. While holding the cookie sheet level, slowly slide the cup to the edge of the cookie sheet.
Step 6. Observe what happens.
Step 7. Refill the cup with water and invert it on the cookie sheet.
Step 8. Quickly pull the cookie sheet straight out from under the cup.
Step 9. Observe the fall of the cup and water.
Step 10. If your school has videotape equipment, you may wish to tape the activity and replay the fall using slow motion or pause controls to study the action at various points of the fall.

FOR FURTHER RESEARCH:

1. As an alternate or a supportive activity, punch a small hole near the bottom of an empty soda pop can. Fill the can with water and seal the hole with your thumb. Position the can over a catch basin and remove your thumb. Observe the water stream. Toss the can through the air to a second catch basin. Try not to make the can tumble or spin in flight. Observe what happens to the water stream. The flight of the can is a good demonstration of the parabolic trajectory followed by NASA's KC-135. (Note: Recycle the can when you are through.)
2. Why should you avoid tumbling or spinning the can?
3. Drop the can while standing on a chair, desk, or ladder. Compare the results with 1.

Activity 4

Accelerometers

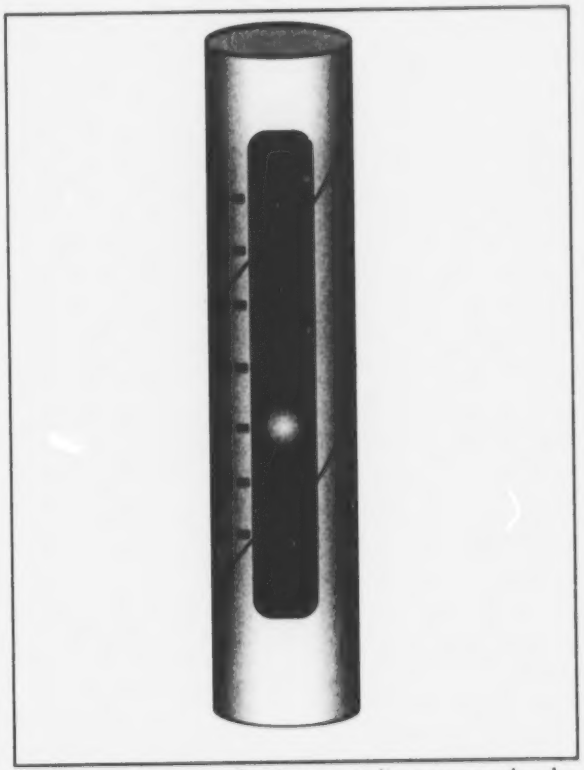
OBJECTIVE:

To measure the acceleration environments created by different motions.

BACKGROUND:

As the Space Shuttle orbits Earth, it collides with thinly spaced gas molecules that produce a minuscule braking effect and eventually causes the Shuttle's orbit to decay. Although not noticeable to astronauts, this braking effect produces a force that is felt by objects inside as an acceleration. *Acceleration* is the rate at which an object's velocity changes with time. *Velocity* is defined as both a speed and a direction. If speed changes, direction changes, or both speed and direction change, the object is said to be undergoing an acceleration. In the case of objects inside of a Space Shuttle, the acceleration causes them to slowly drift from one position in the cabin to another. To avoid this problem objects are usually tethered or stuck to the wall with velcro. However, even a very slight acceleration is a significant problem to sensitive microgravity experiments.

In many microgravity experiments, knowing the magnitude and direction of the acceleration inside an orbiting Space Shuttle is important. At what acceleration do gravity-dependent fluid phenomena, such as buoyancy and sedimentation, become insignificant and other phenomena, such as surface tension, predominate? These and many other questions are



important areas of microgravity research. In this activity, we will experiment with several methods for measuring acceleration.

PROCEDURE:

Step 1. Trim one end of the cardboard tube so that the tube is about 25 centimeters long. Cut a 3 by 15 centimeter window into the side of the tube as shown in the diagram. (The width of the window may have to be modified depending upon the diameter of the tube.)

Step 2. Cut six circles out of the corrugated cardboard equal to the inside diameter of the tube. Test the circles to see that they will fit snugly into the tube ends.

MATERIALS NEEDED:
Cardboard tube
Corugated cardboard
Glue (hot glue works best)
Rubberband
3 lead fishing sinkers (1 oz. "drilled egg")
Marker pen
Metric ruler
Sharp knife or scissors

Step 3. Cut the rubberband so that it forms a long elastic cord. Thread one end of the rubberband through the sinker. You may need a straightened paper clip to help you thread the sinker. Slide the sinker to the middle of the cord and stretch the rubberband. Put a drop of glue in both ends of the sinker. Keep the rubberband stretched until the glue hardens.

Step 4. Punch a small hole through the center of the cardboard circles. Glue three of the circles together. As you glue them, aligning the corrugations in different directions to increase strength. You will end up with two circles, each being three layers thick. When the glue has dried, thread one end of the elastic cord through the holes and knot the end. Repeat this step with the other three circles of cardboard.

Step 5. Insert the cardboard circles into the opposite tube ends and glue them in place. It is not important to have the elastic cord stretched tight at this stage.

Step 6. Lay the tube on its side. Stretch the elastic and tie new knots into its ends so that the lead sinker is positioned in the center of the window. Use the marker pen to mark the edges of the tube where the middle of the sinker is located. Label this position "0."

Step 7. Stand the tube upright and mark where the middle of the sinker is located now. Label this position "1." Turn the tube upside down and mark the tube again where the middle of the sinker is located. Label this position "-1."

Step 8. Using a small piece of tape, attach the second sinker to the first and follow step 7 again. This time, mark the positions "2" and "-2." Add the third sinker to the first two and repeat step 7 again. Label the new positions "3" and -3." Remove the extra sinkers. The accelerometer is now calibrated from three times the pull of gravity to negative three times the pull of gravity.

Step 9. Use the accelerometer in various motion situations to measure the accelerations produced. To operate, the long direction of the accelerometer must be parallel with the direction of the acceleration which, as in the turning automobile example, may or may not be in the direction of motion. Read the acceleration value of the device by comparing the middle of the sinker to the marks on the tube.

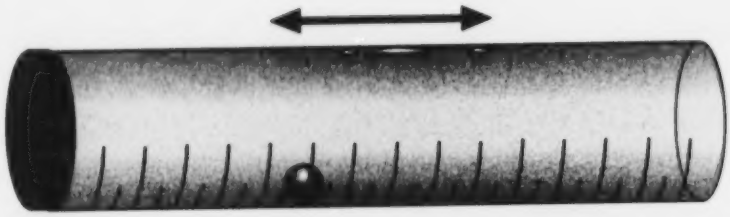
QUESTIONS:

1. What unit is the accelerometer calibrated in? Why did you use the additional sinkers to calibrate the device?
2. What does the device read if you toss it into the air?
3. How does the inner ear work as an accelerometer?
4. Can Faraday's Law be employed to measure acceleration? (Refer to a physics textbook for a discussion of Faraday's Law.)
5. What will the accelerometer read when acceleration stops (such as when a car is moving at a constant speed and direction)?

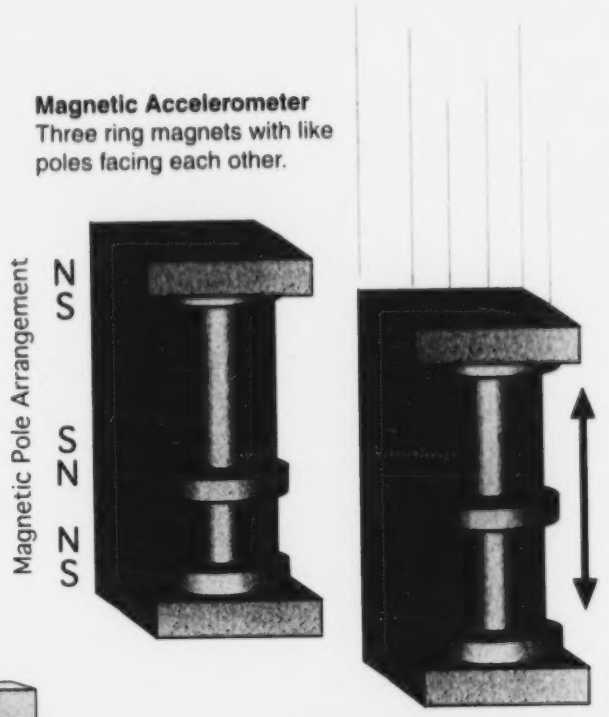
FOR FURTHER RESEARCH:

1. Take the accelerometer to an amusement park and measure the accelerations you experience when you ride a roller coaster and other fast rides.
2. Construct some of the other accelerometers pictured here. How do they work?
3. Design and construct an accelerometer for measuring very slight accelerations such as those that might be encountered on the Space Shuttle.

Falling Sphere Accelerometer
A ball bearing is placed in a graduated cylinder filled with clear liquid soap. How can the ball's falling rate be used to measure acceleration?

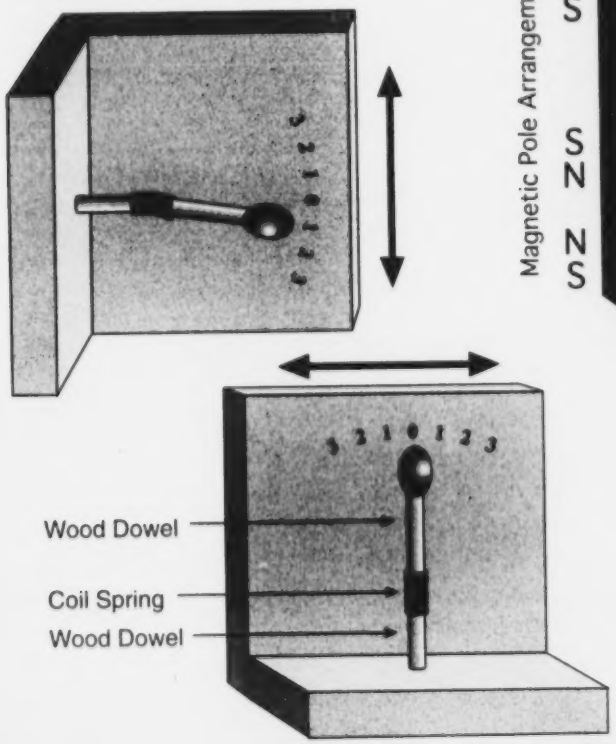


Magnetic Accelerometer
Three ring magnets with like poles facing each other.



Magnetic acclerometer in free fall

Spring Accelerometer
A lead weight is supported by two dowels joined by a spring.



Arrows indicate the direction of the acceleration measurement.

Activity 5

Gravity and Acceleration

OBJECTIVE:

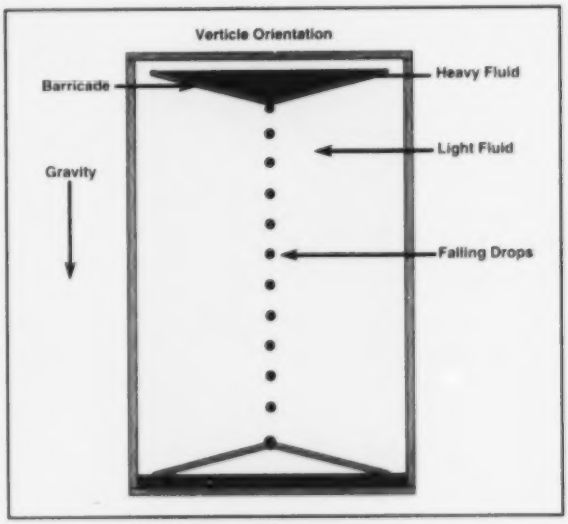
To use a plasma sheet to observe acceleration forces that are experienced on board a space vehicle.

BACKGROUND:

The accelerations experienced on board a space vehicle during flight are vector quantities resulting from forces acting on the vehicle and the equipment. These accelerations have many sources, such as residual gravity, orbiter rotation, vibration from equipment, and crew activity. The equivalent acceleration vector at any one spot in the orbiter is a combination of many different sources and is thus a very complex vector quantity changing over time. The magnitude and direction of the vector is highly dependent on the activities occurring at any time. The accelerations also depend on what has happened in the recent past due to the structural response (e.g., flexing and relaxing) of the vehicle to some activities, such as thruster firing, etc.

On the other hand, the gravity experienced on Earth is a relatively stable acceleration vector quantity because of the dominating large acceleration toward Earth's center. Some activities, such as earthquakes and subsurface magma movements and altitude changes, may perturb local gravitational acceleration.

Gravity and artificial accelerations may be investigated and demonstrated



visually by using a common toy available in many toy, novelty, and museum stores. The toy consists of a clear, flat, plastic box with two liquids of different densities inside. By changing the orientation of the box, droplets of one liquid will pour through the other to the bottom. For the purposes of this activity, the toy will be referred to as a *plasma sheet.*

PROCEDURE:

Step 1. Lay the plasma sheet on its flat side on the stage of an overhead projector. Project the action inside the sheet on a screen for the entire class to observe. The colored liquids will settle into a dispersed pattern across the sheet.

Step 2. Raise one end of the sheet slightly to add a new component to the acceleration vector, and support it

MATERIALS NEEDED:
Plasma sheet toy
Record turntable
File cards
Overhead projector
Slide projector
Projection screen

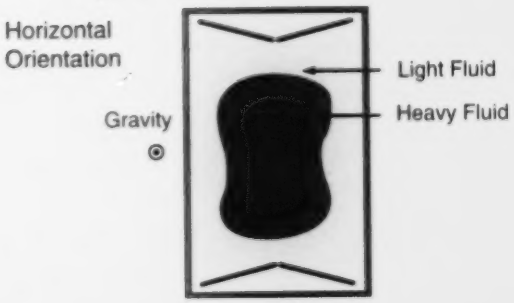
by placing a one-centimeter-thick pile of file cards under the raised end. Observe the movement of the fluids inside.

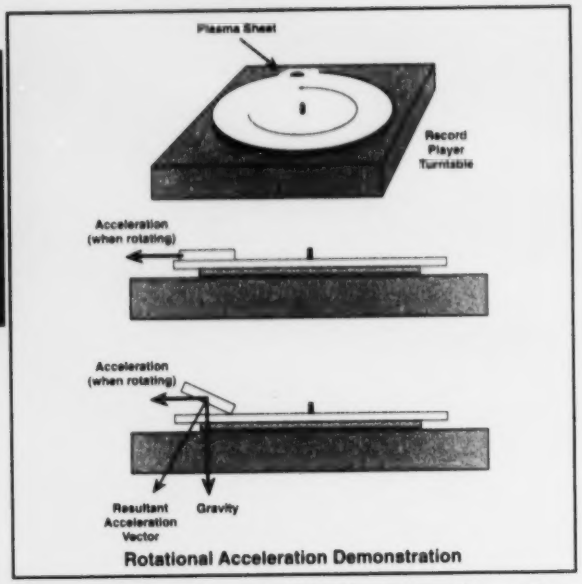
Step 3. Raise the end of the plasma sheet further and support it with another stack of cards. Again, observe the movements of the fluids.

Step 4. Aim the slide projector at the screen. Project a white beam of light at the screen. Stand the plasma sheet on its end in front of the projected beam to cast shadows. Observe the action of the falling liquids.

Step 5. Lay the plasma sheet on its flat side so that the colored liquid will accumulate in the center. Hold the sheet horizontally in your hand and, using your arm as a pendulum, swing the sheet from side to side several times. Observe what happens to the liquid.

Step 6. Lay the plasma sheet on its flat side on a phonograph record turntable. Start the turntable moving. Observe what happens to the liquid.





Rotational Acceleration Demonstration

Step 7. Experiment with elevating the outer edge of the plasma sheet on the turntable until the acceleration vector produces a distribution of liquid similar to the dispersion observed in step 1.

QUESTIONS:

1. What implications do the plasma sheet demonstrations have for scientific researchers interested in investigating microgravity phenomena? How will Space Shuttle orbiter thruster firings and crew movements affect sensitive experiments?
2. How might acceleration vectors be reduced on the Space Shuttle? Would there be any advantage to the quality of microgravity research by conducting that research on International Space Station?

FOR FURTHER RESEARCH:

1. Investigate how scientists measure acceleration vectors in their research.
2. Challenge the students to design a simple and rugged accelerometer that could be used to measure accelerations experienced in a package sent through the U.S. Mail.

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Activity 6

Inertial Balance
Part 1

OBJECTIVE:

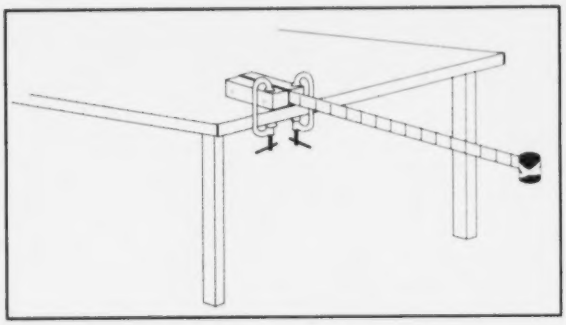
To demonstrate how mass can be measured in microgravity.

BACKGROUND:

The microgravity environment of an orbiting Space Shuttle or space station presents many research challenges for scientists. One of these challenges is the measurement of the mass of experiment samples and subjects. In life sciences research, for example, nutrition studies of astronauts in orbit may require daily monitoring of an astronaut's mass. In materials science research, it may be desirable to determine how the mass of a growing crystal changes daily. To meet these needs, an accurate measurement of mass is vital.

On Earth, mass measurement is simple. The samples and subjects are measured on a scale or beam balance. Calibrated springs in scales are compressed to derive the needed measurement. Beam balances measure an unknown mass by comparison to a known mass (kilogram weights). In both of these methods, the measurement is dependent upon the force produced by Earth's gravitational pull.

In space, neither method works because of the free fall condition of orbit. However, a third method for mass measurement is possible using the principle of inertia. Inertia is the property of matter that causes it to resist acceleration. The



amount of resistance to acceleration is directly proportional to the object's mass.

To measure mass in space, scientists use an inertial balance. An inertial balance is a spring device that vibrates the subject or sample being measured. The frequency of the vibration will vary with the mass of the object and the stiffness of the spring (in this diagram, the yardstick). For a given spring, an object with greater mass will vibrate more slowly than an object with less mass. The object to be measured is placed in the inertial balance, and a spring mechanism starts the vibration. The time needed to complete a given number of cycles is measured, and the mass of the object is calculated.

PROCEDURE:

Step 1. Using the drill and bit to make the necessary holes, bolt two blocks of wood to the opposite sides of one end of the steel yard stick.**Step 2.** Tape an empty plastic film canister to the opposite end of the yardstick. Insert the foam plug.

Step 3. Anchor the wood block end of the inertial balance to a table top with

MATERIALS NEEDED:

Metal yardstick*
2 C-clamps*
Plastic 35mm film canister
Pillow foam (cut in plug shape to fit canister)
Masking tape
Wood blocks
2 bolts and nuts
Drill and bit
Coins or other objects to be measured
Graph paper, ruler, and pencil
Pennies and nickels
Stopwatch
*Available from hardware store

C-clamps. The other end of the yard stick should be free to swing from side to side.

Step 4. Calibrate the inertial balance by placing objects of known mass (pennies) in the sample bucket (canister with foam plug). Begin with just the bucket. Push the end of the yard stick to one side and release it. Using a stopwatch or clock with a second hand, time how long it takes for the stick to complete 25 cycles.

Step 5. Plot the time on a graph above the value of 0. (See sample graph.)

Step 6. Place a single penny in the bucket. Use the foam to anchor the penny so that it does not move inside the bucket. Any movement of the sample mass will result in an error (oscillations of the mass can cause a damping effect). Measure the time needed to complete 25 cycles. Plot the number over the value of 1 on the graph.

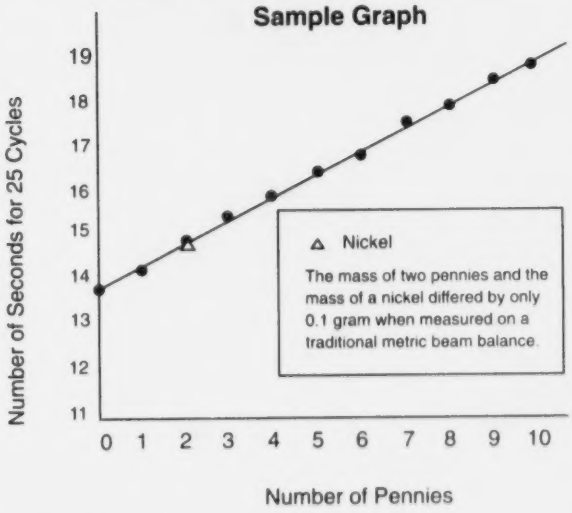
Step 7. Repeat the procedure for different numbers of pennies up to 10.

Step 8. Draw a curve on the graph through the plotted points.

Step 9. Place a nickel (object of unknown mass) in the bucket and measure the time required for 25 cycles. Find the horizontal line that represents the number of vibrations for the nickel. Follow the line until it intersects the graph plot. Follow a vertical line from that point on the plot to the penny scale at the bottom of the graph. This will give the mass of the nickel in "penny" units.

Note: This activity makes use of pennies as a standard of measurement. If you have access to a metric beam balance, you can calibrate the inertial balance into metric mass measurements using the weights as the standards.

Sample Graph



QUESTIONS:

1. Does the length of the ruler make a difference in the results?
2. What are some of the possible sources of error in measuring the cycles?
3. Why is it important to use foam to anchor the pennies in the bucket?

Activity 7

Inertial Balance
Part 2

OBJECTIVE:

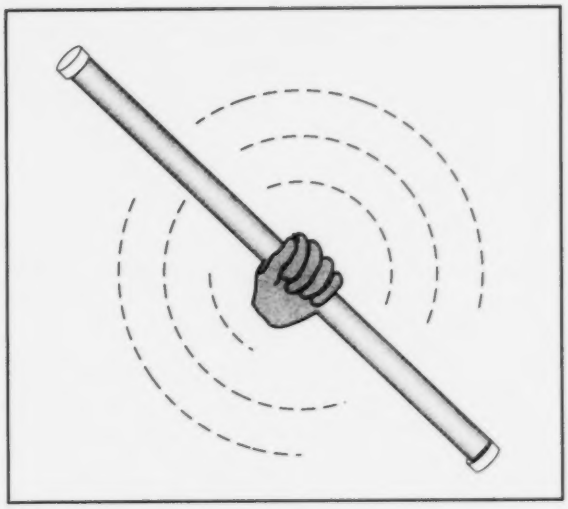
To feel how inertia effects acceleration.

BACKGROUND:

The inertial balance in Part 1 of this activity operates by virtue of the fundamental property of all matter that causes it to resist changes in motion. In the case of the inertial balance, the resistance to motion is referred to as *rotational inertia*. This is because the yardstick pivots at the point on the table where it is anchored and the bucket swings through an arc. Unlike linear motion, the placement of mass in rotational movements is important. Rotational inertia increases with increasing distance from the axis of rotation.

The inertial balance in Part 1 uses a metal yardstick as a spring. The bucket for holding samples is located at the end opposite the axis of rotation. Moving the bucket closer to the axis will make a stiffer spring that increases the sensitivity of the device.

The relationship of the placement of mass to distance from the axis of rotation is easily demonstrated with a set of inertia rods. The rods are identical in appearance and mass and even have identical centers of mass. Yet, one rod is easy to rotate and the other is difficult. The secret of the rods is the location of the mass inside of them. In one rod, the mass is close to the axis of rotation, and in the other, the mass is concentrated at the ends of the rod. Students will be able to feel the difference in rotational inertia between the two rods as they try to rotate them.



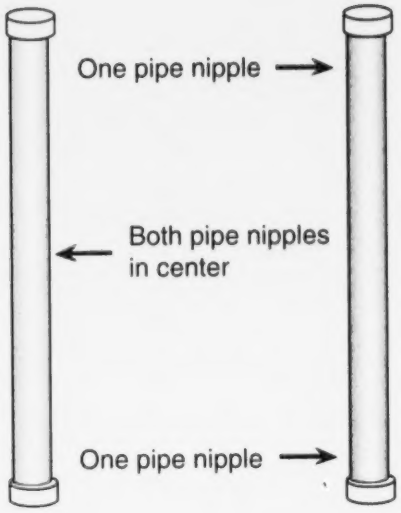
PROCEDURE:

Step 1. Using a saw, cut the PVC tube in half. Smooth out the ends, and check to see that the caps fit the ends.

Step 2. Squeeze a generous amount of silicone rubber sealant into the end of one of the tubes. Slide the nipple into the tube. Using the dowel rod, push the nipple to the middle of the tube. Add sealant to the other end of the tube and insert the second nipple. Position both nipples so that they are touching each other and straddling the center of the tube. Set the tube aside to dry.

MATERIALS NEEDED:

PVC 3/4 in. water pipe
(about 1.5 to 2 m long)
4 iron pipe nipples
(sized to fit inside PVC pipe)
4 PVC caps to fit water pipe
Silicone rubber sealant
Scale or beam balance
Saw
Very fine sand paper
1/2 in. dowel rod



Step 3. Squeeze some sealant into the ends of the second tube. Push the remaining pipe nipples into the ends of the tubes until the ends of the nipples are flush with the tube ends. Be sure there is enough compound to cement the nipples in place. Set the tube aside to dry.

Step 4. When the sealant of both tubes is dry, check to see that the nipples are firmly cemented in place. If not, add additional sealant to complete the cementing. Weigh both rods. If one rod is lighter than the other, add small amounts of sealant to both ends of the rod. Re-weigh. Add more sealant if necessary.

Step 5. Spread some sealant on the inside of the PVC caps. Slide them onto the ends of the tubes to cement them in place.

Step 6. Use fine sand paper to clean the rods.

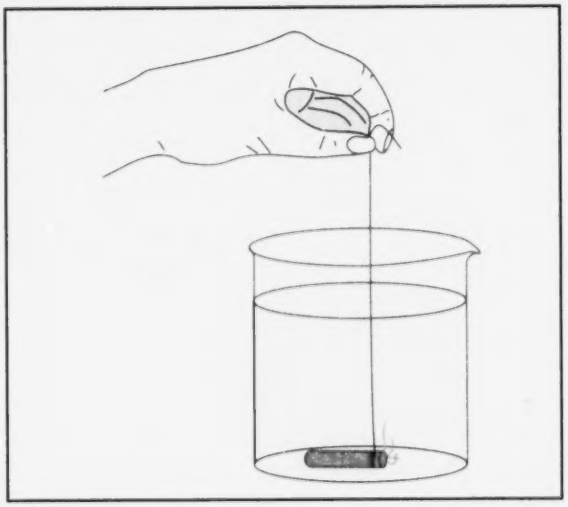
QUESTIONS:

1. How does the placement of mass in the two rods affect the ease with which they are rotated from side to side? Why?
2. If an equal side to side rotational force (known as torque) was exerted on the middle of each rod, which one would accelerate faster?

Payload Commander Rhea Seddon is shown using the Body Mass Measurement Device during the Spacelab Life Sciences-2 mission. The device uses the property of inertia to determine mass.

Activity 8

Gravity-Driven Fluid Flow



OBJECTIVE:

To observe the gravity-driven fluid flow that is caused by differences in solution density.

BACKGROUND:

Many crystals grow in solutions of different compounds. For example, crystals of salt grow in concentrated solutions of salt dissolved in water. Crystals of proteins and other molecules grown in experiments on the Space Shuttle are also grown in similar types of solutions.

Gravity has been shown to cause the fluid around a growing crystal to flow upward. "Up" is defined here as being opposite the direction of gravity. This flow of fluid around the growing crystal is suspected to be detrimental to some types of crystal growth. Such flow may disrupt the arrangement of atoms or molecules on the surface of the growing crystal, making further growth non-uniform.

Understanding and controlling solution flows is vital to studies of crystal growth. The flow appears to be caused by differences in the density of solutions which, in the presence of gravity, create fluid motion around the growing crystal. The solution nearest the crystal surface deposits its chemical material onto the crystal surface, thereby reducing the molecular weight of the solution. The lighter solution tends to float upward, thus creating fluid motion. This experiment recreates the phenomenon of gravity-driven fluid motion and makes it visible.

PROCEDURE:

Step 1. Fill the large glass container with very salty water.

Step 2. Fill the small vial with unsalted water and add two or three drops of food coloring to make it a dark color.

Step 3. Attach a thread to the upper end of the vial, and lower it carefully but quickly into the salt water in the large container. Let the vial sit on the bottom undisturbed.

Step 4. Observe the results.

Step 5. Repeat the experiment using colored salt water in the small vial and unsalted water in the large container.

MATERIALS NEEDED:

Large (500 ml) glass beaker or tall drinking glass
Small (5 to 10 ml) glass vial
Thread
Food coloring
Salt
Spoon or stirring rod

Step 6. Observe the results.

Step 7. Gently remove the two vials and examine the water in them. Are any layers present?

QUESTIONS:

1. Based on your observations, which solution is denser (salt water or unsalted, dyed water)?
2. What do you think would happen if salt water were in both the small vial and the large container? What would happen if unsalted water were in both the small vial and the large container?
3. What results would you expect if the experiment had been performed in a microgravity environment?
4. How does this experiment simulate what happens to a crystal growing in solution?

FOR FURTHER RESEARCH:

1. Repeat the experiment, but replace the water in the small vial with hot, unsalted water. Replace the salt water in the large container with cold, unsalted water.
2. Repeat the experiment with different amounts of salt.
3. Try replacing the salt in the experiment with sugar and/or baking soda.
4. Attempt to control the observed flows by combining the effects of temperature and salinity in each container.
5. Try to observe the fluid flows without using food coloring. You will have to observe carefully to see the effects.

Activity 9

SURFACE TENSION

OBJECTIVE:

To study surface tension and the fluid flows caused by differences in surface tension.

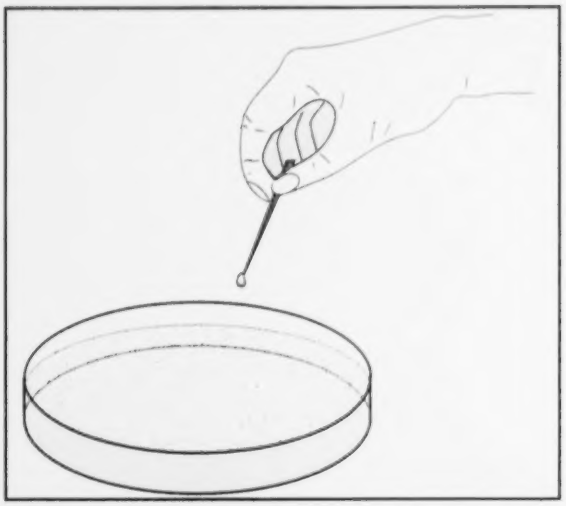
BACKGROUND:

The spherical shape of liquid drops is a result of surface tension. Molecules on the surface of a liquid are attracted to their neighbors in such a way as to cause the surface to behave like an elastic membrane. This can be seen in drops of rain, drops of oil, dewdrops, and water beading on a well-waxed car.

Beneath the surface of a liquid, molecules are attracted to each other from all directions. Because of this attraction, molecules have no tendency to be pulled in any preferred direction. However, a molecule on the surface of a liquid is pulled to each side and inward by neighboring molecules. This causes the surface to adjust to the smallest area possible, a sphere. Surface tension is what allows objects such as needles, razor blades, water bugs, and pepper to float on the surface of liquids.

The addition of a surfactant, such as liquid soap, to a liquid weakens, or reduces, the surface tension. Water molecules do not bond as strongly with soap molecules as they do with themselves. Therefore, the bonding force that enables the molecules to behave like an elastic membrane is weaker.

In a microgravity environment, buoyancy-driven fluid flows and sedimentation are greatly reduced. When this happens,



surface tension can become a dominant force. Furthermore, microgravity makes it easier to study surface tension-driven flows then to study them in a normal gravity environment. An analogy to this process would be like trying to listen to a flutist (the surface tension-driven fluid flows) during a thunderstorm (the buoyancy-driven convection).

PROCEDURE:

Step 1. Fill the beaker, jar, or glass with water.

Step 2. Sprinkle some pepper on the water surface. Observe what happens to the pepper.

Step 3. Stir the water vigorously. Observe what happens to the pepper.

Step 4. Add new water to the container and mix in a few drops of liquid soap. Carefully stir the water to dissolve the detergent but try not to create any bubbles.

MATERIALS NEEDED: *
Beaker, clear jar, or drinking glass
Shallow dish or petri dish
Stirring rod
Water
Black pepper
Clear liquid soap
Toothpick
*per group of students

Step 5. Sprinkle pepper on the water surface. Observe what happens to the pepper.

Step 6. Fill the shallow dish or petri dish with water.

Step 7. Sprinkle some pepper on the surface. Observe any movement of the pepper on the surface.

Step 8. Touch one end of the toothpick into a drop of liquid soap to pick up a small amount of the soap. Carefully touch the end of the toothpick to the surface of the water in the center of the dish. Be careful not to disturb the water. Observe any movement.

Step 9 (optional) Steps 6-8 can be demonstrated to the entire class by placing the dish on the stage of an overhead projector.

QUESTIONS:

1. Why did the pepper float on the water?
2. Why did the pepper sink when the water was stirred?
3. Does the amount of liquid soap affect the results of the experiment? Is more or less detergent better?
4. How does liquid soap enable us to wash dishes?

FOR FURTHER RESEARCH:

1. Make a surface tension-propelled paper boat by cutting a small piece of paper in the shape shown below and floating it on clean water. Touch a small amount of liquid soap to the water in the hole at the back of the boat.
2. Design an experiment to test whether the temperature of a liquid has any effect on surface tension.
3. Try floating needles on water and observe what happens when liquid soap is added.

Surface Tension Paper Boat*
(actual size)

*Note: Make sure that there is a small opening between the notch and the hole.

Activity 10

Candle Flames

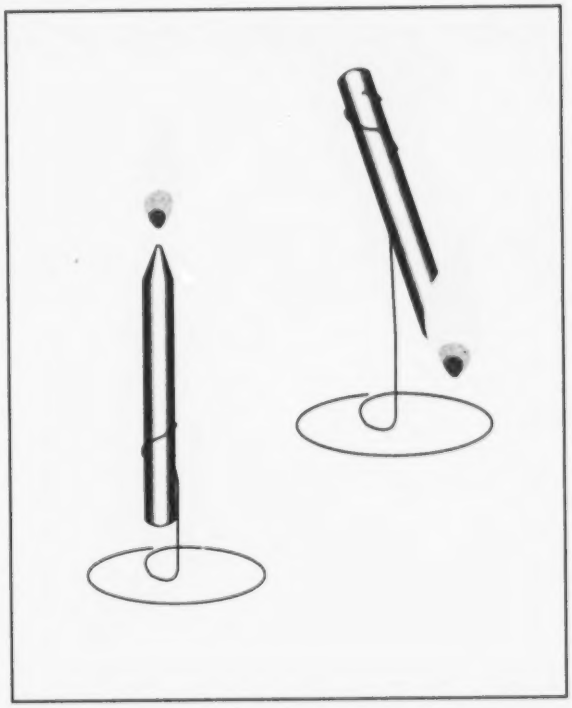
OBJECTIVE:

To illustrate the effects of gravity on the burning rate of candles.

BACKGROUND:

A candle flame is often used to illustrate the complicated physio-chemical processes of combustion. The flame surface itself represents the location where fuel vapor and oxygen mix at high temperature and with the release of heat. Heat from the flame melts the wax (typically a C_{20} to C_{35} hydrocarbon) at the base of the exposed wick. The liquid wax rises by capillary action up the wick, bringing it into closer proximity to the hot flame. This close proximity causes the liquid wax to vaporize. The wax vapors then migrate toward the flame surface, breaking down into smaller hydrocarbons enroute. Oxygen from the surrounding atmosphere also migrates toward the flame surface by diffusion and convection. The survival and location of the flame surface is determined by the balance of these processes.

In normal gravity, buoyancy-driven convection develops due to the hot, less dense combustion products. This action has several effects: (a) the hot reaction products are carried away due to their buoyancy, and fresh oxygen is carried toward the flame zone; (b) solid particles of soot form in the region between the flame and the wick and are convected upward,



where they burn off, yielding the bright yellow tip of the flame; (c) to overcome the loss of heat due to buoyancy, the flame anchors itself close to the wick; (d) the combination of these effects causes the flame to be shaped like a tear drop.

In the absence of buoyancy-driven convection, as in microgravity, the supply of oxygen and fuel vapor to the flame is controlled by the much slower process of molecular diffusion. Where there is no "up" or "down," the flame tends toward sphericity. Heat lost to the top of the candle causes the base of the flame to be quenched, and only a portion of the sphere is seen. The diminished supply of oxygen and fuel causes the flame temperature to

be lowered to the point that little or no soot forms. It also causes the flame to anchor far from the wick, so that the burning rate (the amount of wax consumed per unit time) is reduced.

MATERIALS NEEDED:
Birthday candles (several)
Matches
Balance beam scale (0.1 gm or greater sensitivity)
Clock with second-hand or stopwatch
Wire cutter/pliers
Wire
Small pan to collect dripping wax

PROCEDURE:

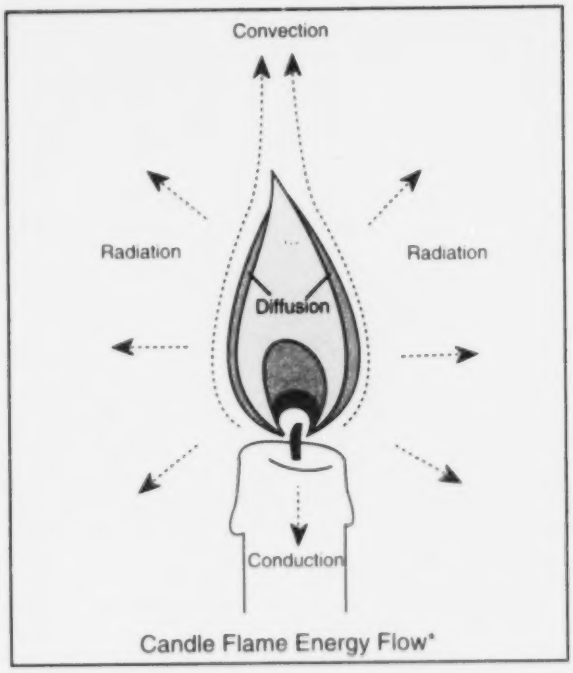
Step 1. Form candle holders from the wire as shown in the diagram. Determine and record the weight of each candle and its holder.
Step 2. Light the "upright" candle and permit it to burn for one minute. As it burns, record the colors, size, and shape of the candle flame.
Step 3. Weigh the candle and holder and calculate how much mass was lost.
Step 4. Place the inverted candle on a small pan to collect dripping wax. (Note: The candle should be inverted to an angle of about 70 degrees from the horizontal. If the candle is too steep, dripping wax will extinguish the flame.)
Step 5. Light the candle and permit it to burn for one minute. As it burns, record the colors, size, and shape of the candle flame.
Step 6. Weigh the candle and holder and calculate how much mass was lost.

QUESTIONS:

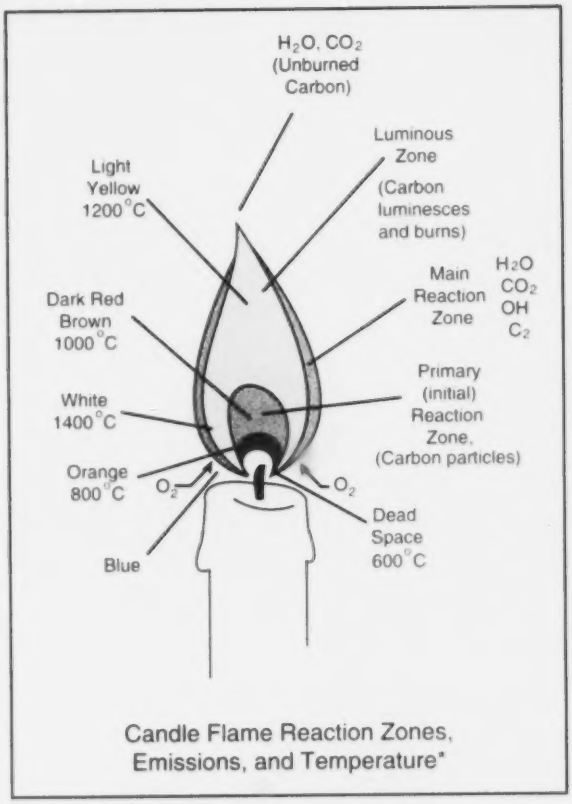
1. Which candle burned faster? Why?
2. How were the colors and flame shapes and sizes different?
3. Why did one candle drip and the other not?
4. Which candle was easier to blow out?
5. What do you think would happen if you burned a candle horizontally?

FOR FURTHER RESEARCH:

1. Burn a horizontally-held candle. As it burns, record the colors, size, and shape of the candle flame. Weigh the candle and calculate how much mass was lost after one minute.
2. Repeat the above experiments with the candles inside a large jar. Let the candles burn to completion. Record the time it takes each candle to burn. Determine how and why the burning rate changed.
3. Burn two candles which are close together. Record the burning rate and weigh the candles. Is it faster or slower than each candle alone? Why?
4. Obtain a copy of Michael Faraday's book, The Chemical History of a Candle, and do the experiments described. (See suggested reading list.)



Candle Flame Energy Flow*



Candle Flame Reaction Zones, Emissions, and Temperature*

*Candle flame diagrams adapted from "The Science of Flames poster," National Energy Foundation, Salt Lake City, UT.

Activity 11

Candle Drop

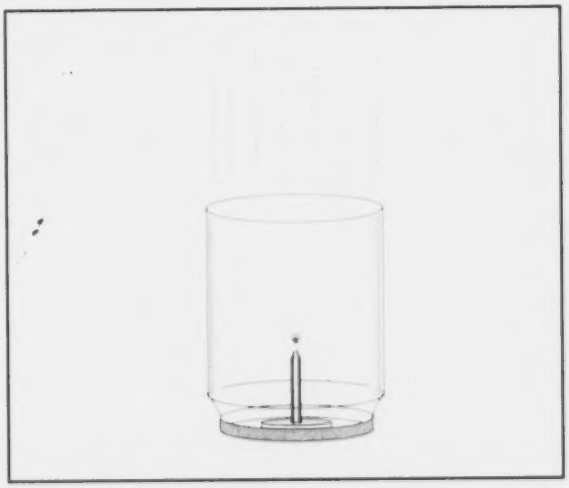
OBJECTIVE:

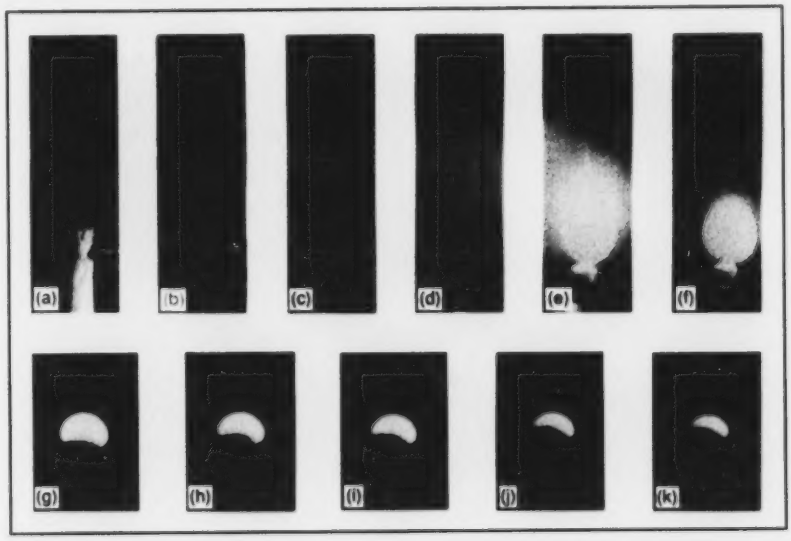
To observe candle flame properties in free fall.

BACKGROUND:

Drop tower and Space Shuttle experiments have provided scientists valuable insights on the dynamics and chemistry of combustion. In both research environments, a flammable material is ignited by a hot wire, and the combustion process is recorded by movie cameras and other data collection devices.

The sequence of pictures beginning at the bottom of this page illustrates a combustion experiment conducted at the NASA Lewis Research Center 150 Meter Drop Tower. These pictures of a candle flame were recorded during a 5-second drop tower test. An electrically-heated wire was used to ignite the candle and then withdrawn one second into the drop. As the pictures illus-





trate, the flame stabilizes quickly, and its shape appears to be constant throughout the remainder of the drop.

Microgravity tests performed on the Space Shuttle furthered this research by determining the survivability of a candle flame. If the oxygen does not diffuse rapidly enough to the flame front, the flame temperature will diminish. Consequently, the heat feedback to and vaporization of the candle wax will be reduced. If the flame temperature and these other processes fall below critical values, the candle flame will be extinguished. Candles on board the first United States Microgravity Laboratory, launched in June 1992, burned from 45 seconds to longer than 60 seconds.

MATERIALS NEEDED:

Clear plastic jar and lid (2 liter volume)*
Wood block
Screws
Birthday-size candles
Matches
Drill and bit
Video camera and monitor (optional)

* Empty large plastic peanut butter jar can be used.

PROCEDURE:

Step 1. Cut a small wood block to fit inside the lid of the jar. Attach the block to the jar lid with screws from the top.

Step 2. Drill a hole in the center of the block to serve as a candle-holder.

Step 3. Insert a candle into the hole. Darken the room. With the lid on the bottom, light the candle and quickly screw the plastic jar over the candle.

Step 4. Observe the shape, brightness, and color of the candle flame. If the oxygen inside the jar is depleted before the observations are completed, remove the jar and flush out the foul air. Relight the candle and seal the jar again.

Step 5. Raise the jar towards the ceiling of the room. Drop the jar with the lit candle to the floor. Position a student near the floor to catch the jar.

Step 6. As the candle drops, observe the shape, brightness, and color of the candle flame. Because the action takes place very quickly, perform several drops to complete the observation process.

QUESTIONS:

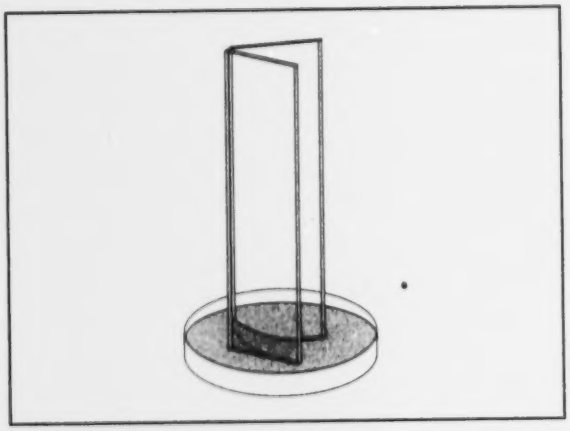
1. Did the candle flame change shape during the drop? If so, what new form did the flame take and why?
2. Did the brightness of the candle flame change? If it did change, why?
3. Did the candle flame go out? If the flame did go out, when did it go out and why?
4. Were the observations consistent from drop to drop?

FOR FURTHER RESEARCH:

1. If videotape equipment is available, videotape the candle flame during the drop. Use the pause control during the playback to examine the flame shape.
2. If a balcony is available, drop the jar from a greater distance than is possible in a classroom. Does the candle continue to burn through the entire drop? For longer drops, it is recommended that a catch basin be used to catch the jar. Fill up a large box or a plastic trash can with styrofoam packing material or loosely crumpled newspaper.

Activity 12

Contact Angle



OBJECTIVE:

To measure the contact angle of a fluid.

BACKGROUND:

In the absence of the stabilizing effect of gravity, fluids partly filling a container in space are acted on primarily by surface forces and can behave in striking, unfamiliar ways. Scientists must understand this behavior to manage fluids in space effectively.

Liquids always meet clean, smooth, solid surfaces in a definite angle, called the contact angle. This angle can be measured by observing the attraction of fluid into sharp corners by surface forces. Even in Earth's gravity, the measurement technique can be observed. If a corner is vertical and sharp enough, surface forces win out over the downward pull of gravity, and the fluid moves upward into the corner. If the angle between the two glass planes is slowly decreased, the fluid the glass is standing in jumps up suddenly when the critical value of the corner angle is reached. In the absence of gravity's effects, the jump would be very striking, with a large amount of fluid pulled into the corner.

PROCEDURE:

Step 1. Place a small amount of distilled water in a dish. (Note: It is important that the dish and the slides are clean.)

Step 2. Place two clean microscope slides into the water so that their ends touch the bottom of the dish and the long slides touch each other at an angle of at least 30 degrees. (Optional step: You may find it easier to manipulate the slides if a tape hinge is used to hold the slides together.)

Step 3. Slowly close the angle between the two slides.

Step 4. Stop closing the angle when the water rises between the slides. Use the protractor to measure the contact angle (angle the water rises up between the slides). Also measure the angle between the two slides.

MATERIALS NEEDED:

Distilled water
Microscope slides
Shallow dish
Protractor
Cellophane tape

QUESTIONS:

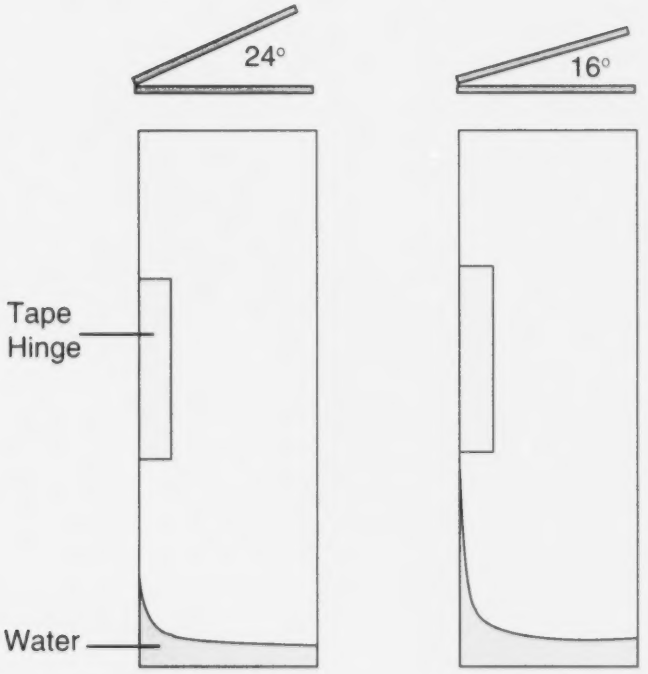
1. What is the mathematical relationship between the contact angle and the angle between the two slides?

   Contact angle = 90 -1/2 wedge angle

2. Why is it important to understand the behavior of fluids in microgravity?

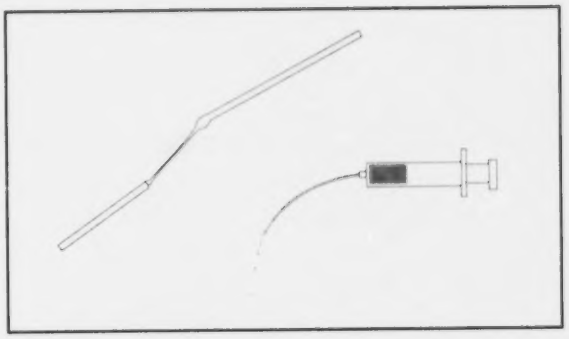
FOR FURTHER RESEARCH:

1. Add some food coloring to the water to make it easier to see. Does the addition of coloring change the contact angle?
2. Measure the contact angle for other liquids. Add a drop of liquid soap or alcohol to the water to see if it alters water's contact angle.
3. Try opening the wedge of the two slides after the water has risen. Does the water come back down easily to its original position?



Activity 13

Fiber Pulling



OBJECTIVE:

To illustrate the effects of gravity and surface tension on fiber pulling.

BACKGROUND:

Fiber pulling is an important process in the manufacture of synthetic fabrics such as nylon and polyester and more recently, in the manufacture of optical fibers for communication networks. Chances are, when you use the telephone for long distance calls, your voice is carried by light waves over optical fibers.

Fibers can be drawn successfully only when the fluid is sufficiently viscous or "sticky." Two effects limit the process: gravity tends to cause the fiber to stretch and break under its own weight, and surface tension causes the fluid to have as little surface area as possible for a given volume. A long slender column of liquid responds to this latter effect by breaking up into a series of small droplets. A sphere has less surface area than a cylinder of the same volume. This effect is known as the "Rayleigh instability" after the work of Lord Rayleigh who explained this behavior mathematically in the late 1800's. A high viscosity slows the fluid motion and allows the fiber to stiffen as it cools before these effects cause the strand to break apart.

Some of the new exotic glass systems under consideration for improved optical fibers are much less viscous in the melt than the quartz used to make the fibers presently in use: this low viscosity makes them difficult to draw into fibers. The destructive effects of gravity could be reduced by forming fibers in space. However, the Rayleigh instability is still a factor in microgravity. Can a reduction in gravity's effects extend the range of viscosities over which fibers can be successfully drawn? This question must be answered before we invest heavily in developing expensive experiment apparatus to test high temperature melts in microgravity. Fortunately, there are a number of liquids that, at room temperature, have fluid properties similar to those of molten glass. This allows us to use common fluids to model the behavior of molten materials in microgravity.

PROCEDURE: (for several demonstrations)

Step 1. While wearing eye and hand protection, use the propane torch or Bunsen burner to melt a blob of glass at one end of a stirring rod. Touch a second rod to the melted blob and pull a thin strand downward. Measure how long the fiber gets before it breaks.
Caution: When broken, the fiber fragments are sharp. Dispose of safely.

MATERIALS NEEDED:

Propane torch or Bunsen burner
Small-diameter glass stirring rods (soft glass)
Disposable syringes (10 ml) without needles
Various fluids (water, honey, corn syrup, mineral oil, and light cooking oil)
Small ball bearings or BBs
Small graduated cylinders or test tubes (at least 5 times the diameter of the ball bearing)
Stopwatch or clock with second-hand
Eye protection
Protective gloves
Metric ruler

Step 2. Squirt a small stream of water from the syringe. Observe how the stream breaks up into small droplets after a short distance. This breakup is caused by the Rayleigh instability of the liquid stream. Measure the length of the stream to the point where the break-up occurs. Do the same for other liquids and compare the results.

Step 3. Touch the end of a cold stirring rod to the surface of a small quantity of water. Try to draw a fiber.

Step 4. Repeat #3 with more viscous fluids, such as honey.

Step 5. Compare the ability to pull strands of the various fluids with the molten glass and with the measurements made in step 2.

Step 6. Pour about 5 centimeters of water into a small test tube. Drop the ball bearing into the tube. Record the time it takes for the ball bearing to reach the bottom. (This is a measure of the viscosity of the fluid.)

Step 7. Repeat #6 for each of the fluids. Record the fall times through each fluid.

QUESTIONS:

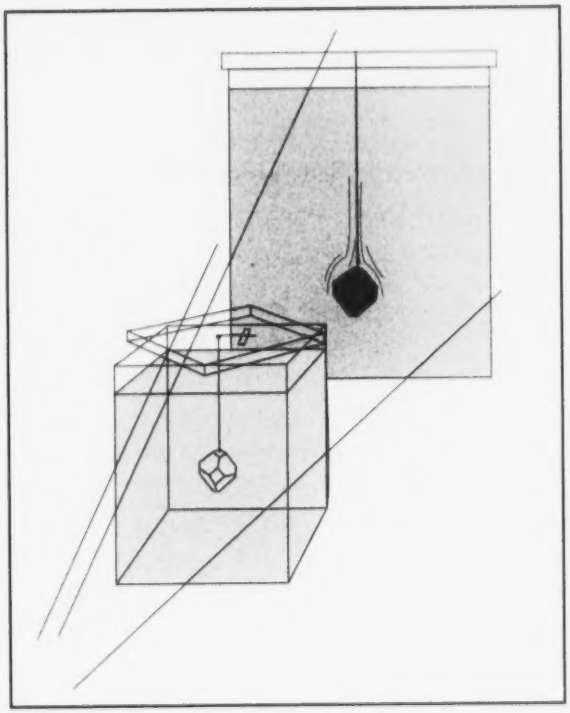
1. Which of the fluids has the closest behavior to molten glass? Which fluid has the least similar behavior to molten glass? (Rank the fluids.)
2. How do the different fluids compare in viscosity (ball bearing fall times)? What property of the fluid is the most important for modeling the behavior of the glass melt?
3. What is the relationship between fiber length and viscosity of the fluid?

FOR FURTHER RESEARCH:

1. With a syringe, squirt a thin continuous stream of each of the test fluids downward into a pan or bucket. Carefully observe the behavior of the stream as it falls. Does it break up? How does it break up? Can you distinguish whether the breakup is due to gravity effects or to the Rayleigh instability? How does the strand break when the syringe runs out of fluid? (For more viscous fluids, it may be necessary to do this experiment in the stairwell with students stationed at different levels to observe the breakup.)
2. Have the students calculate the curved surface area (ignore the area of the end caps) of cylinders with length to diameter ratios of 1, 2, 3, and 4 of equal volume. Now, calculate the surface area of a sphere with the same volume. Since nature wants to minimize the surface area of a given volume of free liquid, what can you conclude by comparing these various ratios of surface area to volume ratios? (Note: This calculation is only an approximation of what actually happens. The cylinder (without the end caps) will have less surface area than a sphere of the same volume until its length exceeds 2.25 times its diameter from the above calculation. Rayleigh's theory calculates the increase in surface area resulting from a disturbance in the form of a periodic surface wave. He showed that for a fixed volume, the surface area would increase if the wavelength was less than π times the diameter, but would decrease for longer waves. Therefore, a long slender column of liquid will become unstable and will break into droplets separated by π times the diameter of the column.)

Activity 14

Crystal Growth



OBJECTIVE:

To observe crystal growth phenomena in a 1-g environment.

BACKGROUND:

A number of crystals having practical applications, such as L-arginine phosphate (LAP) and triglycine sulfate (TGS), may be grown from solutions. In a one-gravity environment, buoyancy-driven convection may be responsible for the formation of liquid inclusions and other defects which can degrade the performance of devices made from these materials. The virtual absence of convection in a microgravity environment may result in far fewer inclusions than in crystals grown on Earth. For this reason, solution crystal growth is an active area of microgravity research.

Crystal growing experiments consist of a controlled growth environment on Earth and an experimental growth environment in microgravity on a spacecraft. In this activity, students will become familiar with crystal growing in 1-g. One or more crystals of alum (aluminum potassium sulfate or $AlK(SO_4)_2 \cdot 12H_2O$ will be grown from seed crystals suspended in a crystal growth solution. With the use of collimated light, shadowgraph views of the growing crystals will reveal buoyancy-driven convective plumes in the growth solution. (Refer to activity 6 for additional background information.)

PROCEDURE:

Step 1. Create a seed crystal of alum by dissolving some alum in a small quantity of water in a beaker. Permit the water to evaporate over several days. Small crystals will form along the sides and bottom of the beaker.

Step 2. Remove one of the small crystals of alum and attach it to a short length of monofilament fishing line with a dab of silicone cement.

Step 3. Prepare the crystal growth solution by dissolving powdered or crystalline alum in a beaker of warm

MATERIALS NEEDED:

Aluminum Potassium Sulfate
$AlK(SO_4)_2 \cdot 12H_2O$*
Square acrylic box**
Distilled water
Stirring rod
Monofiliment fishing line
Silicone cement
Beaker
Slide projector
Projection screen
Eye protection
Hot plate
Thermometer
Balance

* Refer to the chart on the next page for the amount of alum needed for the capacity of the growth chamber (bottle) you use.

** Clear acrylic boxes, about 10x10x13 cm are available from craft stores. Select a box that has no optical distortions.

water. The amount of alum that can be dissolved in the water depends upon the amount of the water used and its temperature. Refer to the table (Alum Solubility in Water) for the quantity required.

Step 4. When no more alum can be dissolved in the water, transfer the solution to the growth chamber acrylic box.

Step 5. Punch a small hole through the center of the lid of the box. Thread the seed crystal line through the hole and secure it in place with a small amount of tape. Place the seed crystal in the box and place the lid on the box at a 45 degree angle. This will expose the surface of the solution to the outside air to promote evaporation. It may be necessary to adjust the length of the line so that the seed crystal is several centimeters above the bottom of the bottle.

Step 6. Set the box aside in a place where it can be observed for several days without being disturbed. If the crystal should disappear, dissolve more alum into the solution and suspend a new seed crystal.

Step 7. Record the growth rate of the crystal by comparing it to a metric ruler. The crystal may also be removed and its mass measured on a balance.

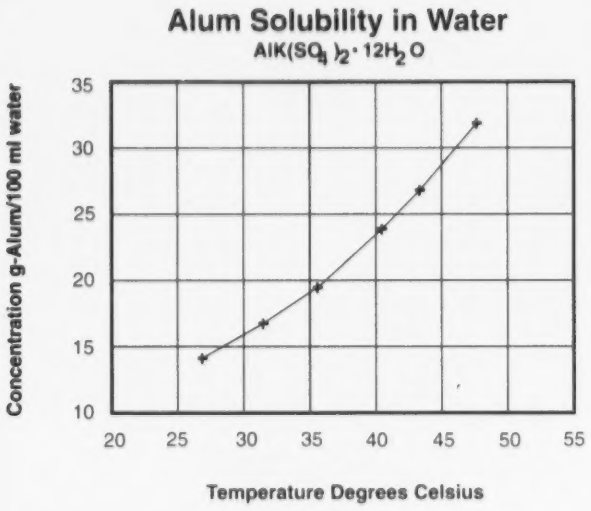
Step 8. Periodically observe the fluid flow associated with the crystal's growth by directing the light beam of a slide projector through the box to a projection screen. Observe plumes around the shadow of the crystal. Convection currents in the growth solution distort the light passing through the growth solution.

QUESTIONS:

1. What is the geometric shape of the alum crystal?
2. What can cause more than one crystal to form around a seed?
3. What do shadowgraph plumes around the growing crystal indicate? Do you think that plumes would form around crystals growing in microgravity?
4. Does the growth rate of the crystal remain constant? Why or why not?
5. What would cause a seed crystal to disappear? Could a crystal decrease in size? Why?
6. What are some of the possible applications for space-grown crystals?

FOR FURTHER RESEARCH:

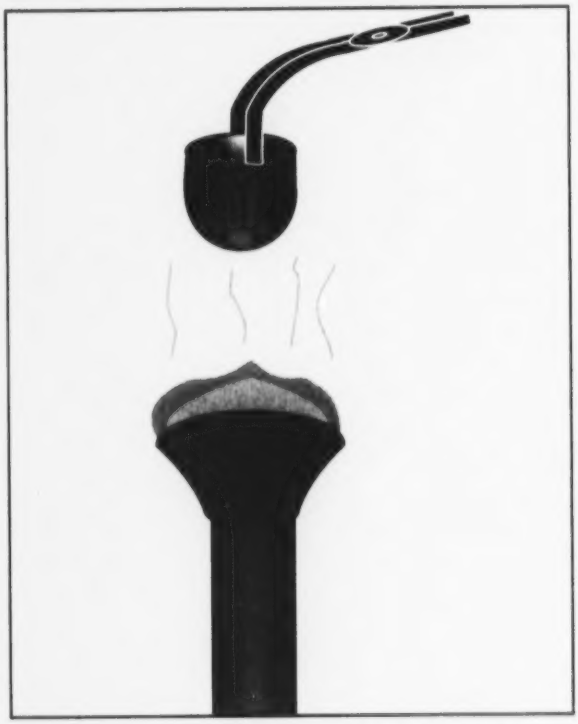
1. Grow additional alum crystals without the cap placed over the box. In one experiment, permit the growth solution to evaporate at room temperature. In another, place the growth chamber in a warm area or even on a hot plate set at the lowest possible setting. Are there any differences in the crystals produced compared to the first one grown? How does the growth rate compare in each of the experiments?
2. Experiment with growing crystals of other chemicals such as table salt, copper sulfate, chrome alum, Rochelle salt, etc. Caution: Become familiar with potential hazards of any of the chemicals you choose and take appropriate safety precautions.
3. Review scientific literature for results from microgravity crystal growing experiments.



Shadowgraph image of a growth plume rising from a growing crystal.

Activity 15

Rapid Crystallization



OBJECTIVE:

To investigate the growth of crystals by two different methods under different temperature conditions.

BACKGROUND:

Crystals are solids composed of atoms, ions, or molecules arranged in orderly patterns that repeat in three dimensions. The geometric form of a crystal visible to the naked eye can be an external expression of the orderly arrangement inside. Many of the unique properties of materials, such as strength and ductility, are a consequence of crystalline structure.

It is easy to get confused about the nature of crystals because the word crystal is frequently misused. For example, a crystal chandelier is not crystal at all. Crystal chandeliers are made of glass. Glass is an *amorphous* material because it lacks a regular interior arrangement of atoms.

Scientists are very interested in growing crystals in microgravity because gravity often interferes with the crystal growing process to indirectly produce different types of defects in the crystal structure. The goal of growing crystals in microgravity is not to develop crystal factories in space but to better understand the crystal growing process and the effects that gravity can have on it.

In this activity, crystal growth will be studied with chemicals that crystallize rapidly in two different ways. The first part of the activity demonstrates the difference between a crystalline material and an amorphous material by manipulating the cooling rate to control how fast the material freezes or solidifies from a molten state. The second part of the activity permits students to observe close-up crystallization from solution. It employs chemical hand warmers.

The hand warmers are sold in full-line camping and hunting stores. They consist of a plastic pouch filled with a food-grade solution of sodium acetate and water. Also in the pouch is a small disk of stainless steel. By snapping the disk, the precipitation and crystallization of the sodium acetate is triggered. As the solid material forms from solution (precipitation) the chemicals release heat (*heat of solution*) that maintains

the pouch temperature at about 54 degrees Celsius for a half hour. This makes the pouch ideal for a hand warmer. Furthermore, the pouch is reusable indefinitely by reheating and dissolving the solid contents again.

The pouch is designed so that at room temperature, the water contains many more molecules of sodium acetate than would normally dissolve at that temperature. This is called a *supersaturated* solution. The solution remains that way until it comes in contact with a seed crystal or some way of rapidly introducing energy into the solution which acts as a trigger for the start of crystallization. Snapping the metal disk inside the pouch delivers a sharp mechanical energy input to the solution that triggers the crystallization process. Crystallization takes place so rapidly that the growth of crystals can easily be observed.

PROCEDURE: (Part 1, Crystalline or Amorphous?)

Note: This activity is a demonstration. Make sure you have adequate ventilation. A small quantity of sulfur fumes may be released. Be sure to wear eye protection while heating the sulfur.

MATERIALS, PART 1

Eye protection
Heavy duty aluminum foil
Scissors
Fat test tube
Tongs
Bunsen Burner
Powdered sulfur
Beaker of cold water
Heat resistant surface
Adequate ventilation

Step 1. Make two disposable aluminum crucibles by wrapping heavy duty aluminum foil around the lower end of a large test tube. Remove the foil and trim each crucible with scissors.

Step 2. Place enough sulfur in each crucible to cover the bottom to about 1 centimeter deep. Using the tongs to hold the first crucible, gently and slowly heat the crucible with a low flame from a Bunsen burner until the sulfur melts. Do not heat the sulfur enough to cause it to ignite. Place the crucible on a heat resistant surface to cool and cover it with a small beaker or another piece of foil.

Step 3. Repeat step 2 with the second crucible. When the sulfur melts, immediately thrust it into a beaker of cold water to cool.

Step 4. When both samples are cool to the touch, peel back the aluminum foil to examine the surface of the sulfur. One sample will show crystalline structure while the other will have a glassy surface. Break each sample in half and examine the edges of the break with a magnifying glass.

QUESTIONS

1. What is the difference between the two sulfur samples?
2. How do the properties of these samples relate to the rate in which they cooled?

FOR FURTHER RESEARCH

1. Compare a piece of granite with a piece of obsidian. Both rocks have approximately the same composition. Why are they different from each other.
2. Learn about some of the applications of crystalline and amorphous materials.

PROCEDURE: (Part 2, Heat Packs)

Note: This activity is an activity involving small groups of students. Because the activity involves boiling water, students should be cautioned to remove the heat packs from the boiler carefully to avoid scalding burns. If you would prefer, handle this part of the activity yourself.

Step 1. Prepare the heat packs by boiling each until all crystals have dissolved. Using tongs, remove the pouches and place them down on towels so that the remaining hot water can be dried off.

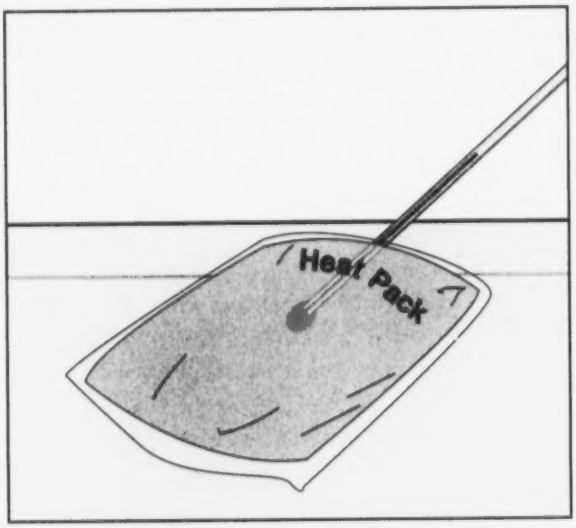
Step 2. Each student group should place a pouch on a styrofoam food tray and slide the bulb of a thermometer under the pack. When the pouch temperature is below 54° C, the internal metal disk can be snapped to trigger crystal growth. Before doing so, the disk should be moved to one corner of the pouch.

Step 3. Using the data sheet on the next page, the students should observe the crystal growth in the pouch.

Step 4. Repeat the activity several times but cool the pouch to different temperatures. To encourage the pouch to cool more rapidly, place it on a hard surface such as a metal cookie sheet or a table top. Return it to the styrofoam to measure its temperature and trigger the crystallization.

QUESTIONS

1. Is there any relationship between the initial temperature of the pouch and the temperature of the pouch during crystallization?
2. Is there a relationship between the initial temperature of the pouch and the time it takes for the pouch to completely solidify?



3. Do other materials, such as water, release heat when they freeze?

FOR FURTHER RESEARCH

1. What do you think would happen if the heat pack were crystallized in microgravity? What effect does gravity have? Hold the pack vertically with the steel disk at the bottom and trigger the solidification. Repeat with the disk at the top. Using two thermometers, measure the temperature of the top and bottom of the pack during crystallization.
2. Try chilling a heat pack pouch in a freezer and then triggering the solidification.
3. Identify other ways the word "crystal" is misused.

MATERIALS, PART 2

Heat pack hand warmers (1 or more per group)
Water boiler (an electric kitchen hot pot can be used)
Styrofoam meat tray (1 per group)
Metric thermometer (1 or more per group)
Observation and data table (1 per student)

Heat Pack Experiment Data Sheet

Name: _____

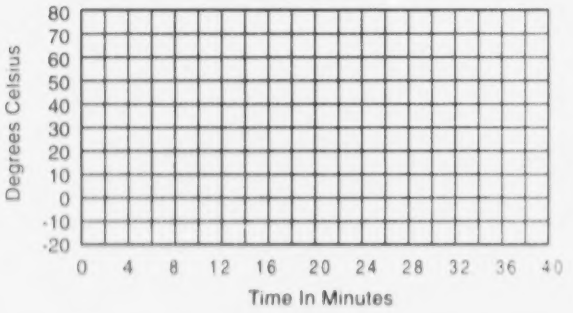
Test Number: _____

Initial Temperature of Pouch: _____

Final Temperature
at end of crystallization: _____

Describe the crystals
(shape, growth rate, size, etc.)

Cooling Graph



Sketch of Crystals

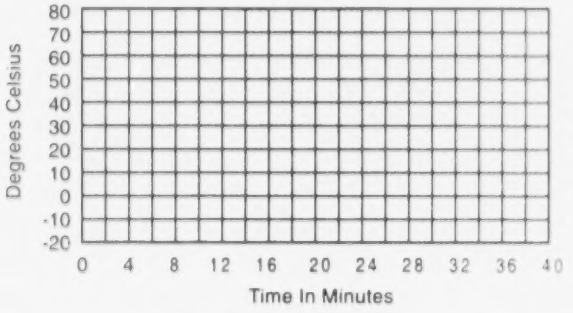
Test Number: _____

Initial Temperature of Pouch: _____

Final Temperature
at end of crystallization: _____

Describe the crystals
(shape, growth rate, size, etc.)

Cooling Graph



Sketch of Crystals

Activity 16

Microscopic Observation of Crystal Growth

OBJECTIVE:

To observe crystal nucleation and growth rate during directional solidification.

BACKGROUND:

Directional solidification refers to a process by which a liquid is transformed (by freezing) into a solid through the application of a temperature gradient in which heat is removed from one direction. A container of liquid will turn to a solid in the direction the temperature is lowered. If this liquid has a solute present, typically, some of the solute will be rejected into the liquid ahead of the liquid/solid interface. However, this rejection does not always occur, and in some cases, the solute is incorporated into the solid. This phenomenon has many important consequences for the solid. As a result, solute rejection is studied extensively in solidification experiments.

The rejected material tends to build up at the interface to form a mass boundary layer. This experiment demonstrates what happens when the growth rate is too fast and solute in the boundary layer is trapped.

Fluid flow in the melt can also affect the buildup of the mass boundary layer. On Earth, fluids that expand become less dense. This causes a vertical flow of liquid which will interfere with the mass boundary layer. In space, by avoiding this fluid flow, a more uniform mass boundary layer will be achieved. This, in turn, will improve the uniformity with which the solute is incorporated into the growing crystal.

PROCEDURE:

Observations of Mannite*

Step 1. Place a small amount of mannite on a microscope slide and place the slide on a hot plate. Raise the temperature of the hot plate until the mannite melts. **Caution: Be careful not to touch the hotplate or heated slide. Handle the slide with forceps.**

MATERIALS NEEDED:

Bismarck Brown Y**
Mannite (d-Mannitol)
$HOCH_2(CHOH)_4CH_2OH$*
Salol (Phenyl Salicylate)
$C_{13}H_{10}O_3$**
Microprojector
Student microscopes (alternate to microprojector)
Glass microscope slides with cover glass
Ceramic bread and butter plate
Refrigerator
Hot plate
Desktop coffee cup warmer
Forceps
Dissecting needle
Spatula
Eye protection
Gloves
Marker pen for writing on slides

Step 2. After melting, cover the mannite with a cover glass and place the slide on a ceramic bread-and-butter plate that has been chilled in a refrigerator. Permit the liquid mannite to crystallize.

Step 3. Observe the sample with a microprojector. Note the size, shape, number, and boundaries of the crystals.

Step 4. Prepare a second slide, but place it immediately on the microprojector stage. Permit the mannite to cool slowly. Again, observe the size, shape, and boundaries of the crystals. Mark and save the two slides for comparison using student microscopes. Forty power is sufficient for comparison. Have the students make sketches of the crystals on the two slides and label them by cooling rate.

Observations of Salol

Step 5. Repeat the procedure for mannite (steps 1-4) with the salol, but do not use glass cover slips. Use a desktop coffee cup warmer to melt the salol. It may be necessary to add a seed crystal to the liquid on each slide to start the crystallization. Use a spatula to carry the seed to the salol. If the seed melts, wait a moment and try again when the liquid is a bit cooler. (If the microprojector you use does not have heat filters, the heat from the lamp may remelt the salol before crystallization is completed. The chemical thymol ($C_{10}H_{14}O$) may be substituted for the salol. Avoid breathing its vapors. Do not substitute thymol for salol if student microscopes are used.)

Step 6. Prepare a new salol slide and place it on the microprojector stage. Drop a tiny seed crystal into the melt and observe the solid-liquid interface.

Step 7. Remelt the salol on the slide and sprinkle a tiny amount of Bismarck Brown on the melt. Drop a seed crystal into the melt and observe the motion of the Bismarck Brown granules. The granules will make the movements of the liquid visible. Pay close attention to the granules near the growing edges and points of the salol crystals. How is the liquid moving?

NOTES ON CHEMICALS USED:

Bismarck Brown Y

Bismarck Brown is a stain used to dye bone specimens for microscope slides. Because Bismarck Brown is a stain, avoid getting it on your fingers. Bismarck Brown is water solulable.

Mannite (d-Mannitol)

$HOCH_2(CHOH)_4CH_2OH$

Mannite has a melting point of approximately 168° C. It may be harmful if inhaled or swallowed. **Caution: Wear eye protection and gloves when handling this chemical. Conduct the experiment in a well ventilated area.**

Salol (Phenyl Salicylate)

$C_{13}H_{10}O_3$

It has a melting point of 43° C. It may irritate eyes. **Caution: Wear eye protection.**

QUESTIONS:

1. What happens to crystals when they begin growing from multiple nuclei?
2. Are there any differences in crystals that form from a melt that has cooled rapidly and from one that has cooled slowly? What are those differences?
3. What happens to the resulting crystals when impurities exist in the melt?
4. What caused the circulation patterns of the liquid around the growing crystal faces? Do you think these circulation patterns affect the atomic arrangements of the crystals?
5. How do you think the growth of the crystals would be affected by growing them in microgravity?

FOR FURTHER RESEARCH:

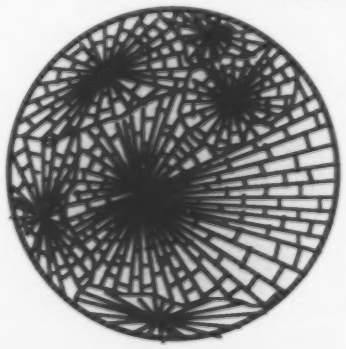
1. Design a crystal growing experiment that could be flown in space. The experiment should be self-contained and the only astronaut involvement that of turning on and off a switch.
2. Design a crystal growing experiment for space flight that requires astronaut observations and interpretations.
3. Research previous crystal growing experiments in space and some of the potential benefits researchers expect from space-grown crystals.

* Because of the higher temperatures involved, the mannite slides should be prepared by the teacher. If you wish, you may process the mannite slides at home in an oven. By doing so, you will eliminate the need for a hotplate. Mark the two prepared slides by cooling rate.

** Obtain the smallest quantities available from chemical supply houses.

Sample Microscope Sketches

Mannite Crystallization



Slow Cooling

Fast Cooling

Glossary

Acceleration - The rate at which an object's velocity changes with time.

Buoyancy-Driven Convection - Convection created by the difference in density between two or more fluids in a gravitational field.

Convection - Energy and/or mass transfer in a fluid by means of bulk motion of the fluid.

Diffusion - Intermixing of atoms and/or molecules in solids, liquids, and gases due to a difference in composition.

Drop Tower - Research facility that creates a microgravity environment by permitting experiments to free fall through an enclosed vertical tube.

Exothermic - Releasing heat.

Fluid - Anything that flows (liquid or gas).

Free Fall - Falling in a gravitational field where the acceleration is the same as that due to gravity alone.

G - Universal Gravitational Constant ($6.67X10^{-11}$ Nm^2/kg^2)

g - The acceleration Earth's gravitational field exerts on objects at Earth's surface. (approximately 9.8 meters per second squared)

Gravitation - The attraction of objects due to their masses.

Inertia - A property of matter that causes it to resist changes in velocity.

Law of Universal Gravitation - A law stating that every mass in the universe attracts every other mass with a force proportional to the product of their masses and inversely proportional to the square of the distances between their centers.

Microgravity (μg) - An environment that imparts to an object a net acceleration that is small compared with that produced by Earth at its surface.

Parabolic Flight Path - The flight path followed by airplanes in creating a microgravity environment (the shape of a parabola).

Skylab - NASA's first orbital laboratory that was operated in 1973 and 1974.

Spacelab - A scientific laboratory developed by the European Space Agency that is carried into Earth orbit in the Space Shuttle's payload bay.

NASA Educational Materials

NASA publishes a variety of educational resources suitable for classroom use. The following resources specifically relate to microgravity and living, working, and science research in the microgravity environment. Resources are available from different sources as noted.

Educational Videotapes

Educational videotapes and slide sets are obtainable through CORE.

Microgravity, from the NASA Educational Satellite Videoconference Series.
Length: 60:00
Grades: 4-12
Application: Chemistry, Life Science, Physical Science
NASA astronauts, scientists, and aerospace education specialists present microgravity concepts, discuss scientific research, and engage in interactive hands-on activities with students/teachers that call in. 1992

Gravity and Life, Episode 2 of NASA Biology: On Earth and In Space Series.
Length: 30:00
Grades 8-12
Application: Life Science
Dr. Richard Keefe, Professor of Anatomy, Case Western Reserve University, explains the role of gravity in the development of life. 1987

Gravity - A Force of Nature, Episode 3 of What's In the News-Space
Length: 15:00
Grades: 4-12
Application: Physical Science
Explains the concept of universal gravity, microgravity, and weightlessness using examples from Earth such as a roller coaster and from space such as Skylab and Space Shuttle acrobatics. 1993

Slides

Microgravity Science
Grades: 8-12
This set of 24 slides comes illustrates the basic concepts of microgravity and describes four areas of microgravity research, including: biotechnology, combustion science, fluid physics, and materials science. 1994

Educational Software

Microgravity
Grades: 4-8
This tutorial is one of a series that NASA Jet Propulsion Laboratory developed to motivate teachers and students to study science, mathematics, and technology. Students use inverses, squares, and ratios to calculate gravity in space and orbits. *Apple II Software.*

NASA Publications

To obtain NASA publications, contact the NASA Field Center that the desired publication specifies. A listing of addresses for NASA Field Centers appears on pages 71-72.

NASA (1980), Materials Processing In Space: Early Experiments, Scientific and Technical Information Branch, NASA Headquarters, Washington, DC.

NASA (1982), Spacelab, EP-165, NASA Headquarters, Washington, DC.

NASA (1976 -Present), Spinoff , NASA Headquarters, Washington, DC. (annual publication).

NASA (1991), "International Microgravity Laboratory-1, MW 010/12-91," Flight Crew Operations Directorate, NASA Johnson Space Center, Houston, TX.

NASA (1994), "Microgravity News," Microgravity Science Outreach, Mail Stop 359, NASA Langley Research Center, Hampton, VA (quarterly newsletter)

NASA (1992), "Mission Highlights STS-42," MHL 010/2-92, Flight Crew Operations Directorate, NASA Johnson Space Center, Houston, TX.

NASA (1992), "Mission Highlights STS-50," MHL 013/7-92, Flight Crew Operations Directorate, NASA Johnson Space Center, Houston, TX.

NASA (1994), "Mission Highlights STS-62," MHL 024/4-94, Flight Crew Operations Directorate, NASA Johnson Space Center, Houston, TX.

NASA (1994), "Mission Highlights STS-65," MHL 028/9-94, Flight Crew Operations Directorate, NASA Johnson Space Center, Houston, TX.

NASA (1991), "United States Microgravity Laboratory-1," MW 013/6-92, Flight Crew Operations Directorate, NASA Johnson Space Center, Houston, TX.

NASA (1988), Science in Orbit — The Shuttle and Spacelab Experience: 1981-1986, NASA Marshall Space Flight Center, Huntsville, AL.

Suggested Reading

Books

Faraday, M., (1988), The Chemical History of a Candle, Chicago Review Press, Chicago, IL.

Halliday, D. & Resnick, R., (1988), Fundamentals of Physics, John Wiley & Sons, Inc., New York, NY.

Holden, A. & Morrison, P., (1982), Crystals and Crystal Growing, The MIT Press, Cambridge, MA.

Lyons, J., (1985), Fire, Scientific American, Inc., New York, NY.

American Institute of Aeronautics and Astronautics(1981), Combustion Experiments in a Zero-gravity Laboratory, New York, NY.

Periodicals

Chandler, D., (1991), "Weightlessness and Microgravity," Physics Teacher, v29n5, pp312-313.

Cornia, R., (1991), "The Science of Flames," The Science Teacher, v58n8, pp43-45.

Frazer, L., (1991), "Can People Survive in Space?," Ad Astra, v3n8, pp14-18.

Howard, B., (1991), "The Light Stuff," Omni, v14n2, pp50-54.

Noland, D., (1990), "Zero-G Blues," Discover, v11n5, pp74-80.

Pool, R., (1989), "Zero Gravity Produces Weighty Improvements," Science, v246n4930, p580.

Space World, (1988), "Mastering Microgravity," v7n295, p4.

Science News, (1989), "Chemistry: Making Bigger, Better Crystals," v136n22, p349.

Science News, (1989), "Making Plastics in Galileo's Shadow," v136n18, p286.

USRA Quarterly, (1992), "Can You Carry Your Coffee Into Orbit?," Winter-Spring.

NASA Educational Resources

NASA Spacelink: An Electronic Information System

NASA Spacelink is an electronic information system designed to provide current educational information to teachers, faculty, and students. Spacelink offers a wide range of materials (computer text files, software, and graphics) related to the space program. Documents on the system include: science, mathematics, engineering, and technology education lesson plans, historical information related to the space program, current status reports on NASA projects, news releases, information on NASA edcuational programs, NASA educational publications, and other materials, such as computer software and images, chosen for their educational value and relevance to space education. The system may be accessed by computer through direct-dial modem or the Internet.

Spacelink's modem line is (205) 895-0028.
Data format 8-N-1, VT-100 terminal emulation required.
The Internet TCP/IP address is 192.149.89.61
Spacelink fully supports the following Internet services:

World Wide Web:	http://spacelink.msfc.nasa.gov
Gopher:	spacelink.msfc.nasa.gov
Anonymous FTP:	spacelink.msfc.nasa.gov
Telnet:	spacelink.msfc.nasa.gov (VT-100 terminal emulation required)

For more information contact:
Spacelink Administrator
Education Programs Office
Mail Code CL 01
NASA Marshall Space Flight Center
Huntsville, AL 35812-0001
Phone: (205) 961-1225

NASA Education Satellite Videoconference Series

The Education Satellite Videoconference Series for Teachers is offered as an inservice education program for educators through the school year. The content of each program varies, but includes aeronautics or space science topics of interest to elementary and secondary teachers. NASA program managers, scientists, astronauts, and education specialists are featured presenters. The videoconference series is free to registered educational institutions. To participate, the institution must have a C-band satellite receiving system, teacher release time, and an optional long distance telephone line for interaction. Arrangements may also be made to receive the satellite signal through the local cable television system. The programs may be videotaped and copied for later use. For more information, contact:

NASA... On the Cutting Edge
Teaching From Space Program
Oklahoma State University
308 CITD, Room A
Stillwater, OK 74078
E-Mail: nasaedutv@smtpgate.osu.hq.nasa.gov

NASA Television

NASA Television features: Space Shuttle mission coverage, live special events, interactive education videoconferences, electronic field trips, aviation and space news, and historical NASA footage. Programming has three blocks—Education File, History File, and News Video File—repeated at intervals 24 hours a day. The *Education File* features programming for teachers and students on science, mathematics, and technology. You and your class can investigate exciting NASA research endeavors in aeronautics, microgravity, planetary sciences, human exploration of space, Earth systems, robotics, and more. Educators are welcome to videotape NASA TV.

NASA Television is transmitted on:
Spacenet 2 (a C-band satellite) on transponder 5
channel 8
69 degrees West with horizontal polarization
frequency 3880.0 Megahertz
audio on 6.8 megahertz

For more information contact:
NASA Television
NASA Headquarters
Code P-2
Washington, DC 20546

NASA Teacher Resource Center Network

To make additional information available to the education community, the NASA Education Division has created the NASA Teacher Resource Center (TRC) network. TRCs contain a wealth of information for educators: publications, reference books, slide sets, audio cassettes, videotapes, telelecture programs, computer programs, lesson plans, and teacher guides with activities. Because each NASA field center has its own areas of expertise, no two TRCs are exactly alike. Phone calls are welcome if you are unable to visit the TRC that serves your geographic area. A list of the centers and the geographic regions they serve starts at the bottom of this page.

Regional Teacher Resource Centers (RTRCs) offer more educators access to NASA educational materials. NASA has formed partnerships with universities, museums, and other educational institutions to serve as RTRCs in many states. Teachers may preview, copy, or receive NASA materials at these sites. A complete list of RTRCs is available through CORE.

NASA Central Operation of Resources for Educators (CORE) was established for the national and international distribution of NASA-produced educational materials in audiovisual format. Educators can obtain a catalogue of these materials and an order form by written request, on school letterhead to:

NASA CORE
Lorain County Joint Vocational School
15181 Route 58 South
Oberlin, OH 44074
Phone: (216) 774-1051, Ext. 293 or 294

IF YOU LIVE IN:		Center Education Program Officer	Teacher Resource Center
Alaska Arizona California Hawaii Idaho Montana	Nevada Oregon Utah Washington Wyoming	Mr. Garth A. Hull Chief, Education Programs Branch Mail Stop 204-12 **NASA Ames Research Center** Moffett Field, CA 94035-1000 PHONE: (415) 604-5543	NASA Teacher Resource Center Mail Stop T12-A **NASA Ames Research Center** Moffett Field, CA 94035-1000 PHONE: (415) 604-3574
Connecticut Delaware District of Columbia Maine Maryland Massachusetts	New Hampshire New Jersey New York Pennsylvania Rhode Island Vermont	Educational Programs Code 130 **NASA Goddard Space Flight Center** Greenbelt, MD 20771-0001 PHONE: (301) 286-7206	NASA Teacher Resource Laboratory Mail Code 130.3 **NASA Goddard Space Flight Center** Greenbelt, MD 20771-0001 PHONE: (301) 286-8570
Colorado Kansas Nebraska New Mexico	North Dakota Oklahoma South Dakota Texas	Dr. Robert W. Fitzmaurice Center Education Program Officer Education & Information Services Branch - AP2 2101 NASA Road 1 **NASA Johnson Space Center** Houston, TX 77058-3696 PHONE: (713) 483-1257	NASA Teacher Resource Room Mail Code AP2 2101 NASA Road 1 **NASA Johnson Space Center** Houston, TX 77058-3696 PHONE: (713) 483-8696
Florida Georgia Puerto Rico Virgin Islands		Dr. Steve Dutczak Chief, Education Services Branch Mail Code PA-ESB **NASA Kennedy Space Center** Kennedy Space Center, FL 32899-0001 PHONE: (407) 867-4444	NASA Educators Resource Laboratory Mail Code ERL **NASA Kennedy Space Center** Kennedy Space Center, FL 32899-0001 PHONE: (407) 867-4090

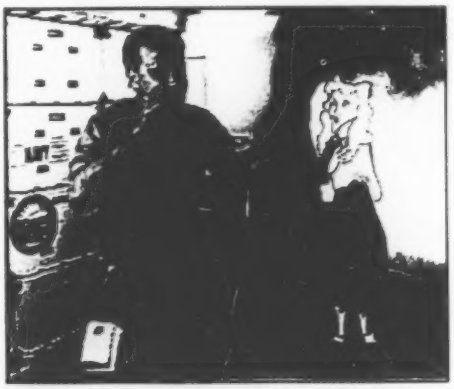
IF YOU LIVE IN:	Center Education Program Officer	Teacher Resource Center
Kentucky North Carolina South Carolina Virginia West Virginia	Ms. Marchelle Canright Center Education Program Officer Mail Stop 400 **NASA Langley Research Center** Hampton, VA 23681-0001 PHONE: (804) 864-3313	NASA Teacher Resource Center for **NASA Langley Research Center** Virginia Air and Space Center 600 Settler's Landing Road Hampton, VA 23699-4033 PHONE: (804)727-0900 x 757
Illinois Minnesota Indiana Ohio Michigan Wisconsin	Ms. Jo Ann Charleston Acting Chief, Office of Educational Programs Mail Stop 7-4 **NASA Lewis Research Center** 21000 Brookpark Road Cleveland, OH 44135-3191 PHONE: (216) 433-2957	NASA Teacher Resource Center Mail Stop 8-1 **NASA Lewis Research Center** 21000 Brookpark Road Cleveland, OH 44135-3191 PHONE: (216) 433-2017
Alabama Louisiana Arkansas Missouri Iowa Tennessee	Mr. Jim Pruitt Acting Director, Education Programs Office Mail Stop CL 01 **NASA Marshall Space Flight Center** Huntsville, AL 35812-0001 PHONE: (205) 544-8800	NASA Teacher Resource Center for **NASA Marshall Space Flight Center** U.S. Space and Rocket Center P.O. Box 070015 Huntsville, AL 35807-7015 PHONE: (205) 544-5812
Mississippi	Dr. David Powe Manager, Educational Programs Mail Stop MA00 **NASA John C. Stennis Space Center** Stennis Space Center, MS 39529-6000 PHONE: (601) 688-1107	NASA Teacher Resource Center Building 1200 **NASA John C. Stennis Space Center** Stennis Space Center, MS 39529-6000 PHONE: (601) 688-3338
The Jet Propulsion Laboratory (JPL) serves inquiries related to space andplanetary exploration and other JPL activities.	Dr. Fredrick Shair Manager, Educational Affairs Office Mail Code 183-900 **NASA Jet Propulsion Laboratory** 4800 Oak Grove Drive Pasadena, CA 91109-8099 PHONE: (818) 354-8251	NASA Teacher Resource Center JPL Educational Outreach Mail Stop CS-530 **NASA Jet Propulsion Laboratory** 4800 Oak Grove Drive Pasadena, CA 91109-8099 PHONE: (818) 354-6916
California (mainly cities near Dryden Flight Research Facility)		NASA Teacher Resource Center Public Affairs Office (Trl. 42) **NASA Dryden Flight Research Facility** Edwards, CA 93523-0273 PHONE: (805) 258-3456
Virginia and Maryland's Eastern Shores		NASA Teacher Resource Lab NASA Goddard Space Flight Center **Wallops Flight Facility** Education Complex - Visitor Center Building J-17 Wallops Island, VA 23337-5099 Phone: (804) 824-2297/2298

Liftoff To Learning Educational Videotape Series

To obtain a copy of any of these videotapes and the accompanying Video Resource Guide, or for more information on the Liftoff to Learning Educational Videotape Series, contact NASA Central Operation of Resources for Educators (CORE). See page 71.

Living In Space demonstrates what it is like to live and work in space. Viewers are invited by the Space Shuttle Crew to join the astronauts as they go through their daily routine living onboard the Space Shuttle. Students see the similarities and differences in eating, exercising, relaxing, maintaining personal hygience, sleeping, and working in space versus on Earth.

Grade Levels: K-4
Application: Life Sciences, Physical Science
Length: 10:00



Newton In Space offers an introduction to Isaac Newton's Laws of Motion and how these laws apply to space flight. The program explains the difference between weight and mass, the basic prin-ciples of balanced and unbalanced forces, action and opposite reac-tions, and how the three laws of motions affect the way a rocket operates. Using the microgravity environment of Earth orbit, Space Shuttle astronauts conduct simple force and motion demonstrations in ways not possible on Earth.

Grade Levels: 5-8
Application: Physical Science
Length: 12:37

Space Basics answers basic questions about space flight including: how spacecraft travel into space; how spacecraft remain in orbit; why astronauts float in space; and how spacecraft return to Earth. Viewers learn how English scientist Isaac Newton formulated the basic science behind Earth orbit more than 300 years ago.

Grade Levels: 5-8
Application: History, Physical Science, Technology
Length: 20:55

Toys In Space II provides a hands-on way for students to investigate principles of mathematics and science that make many common toys function. The Space Shuttle crew invite students to experiment with similar toys in their classroom and hypothesize how these same toys will operate in microgravity. Scenes of the astronauts operating the toys in space serve as data for students to confirm or reject their hypotheses.

Grade Levels: K-12
Application: Mathematics, Physical Science, Technology
Length: 20:55

Educators and scientists at the National Aeronautics and Space Administration would appreciate your taking a few minutes to respond to the statements and questions below. Please affix proper postage and return by mail.

SA	Strongly Agree
A	Agree
D	Disagree
SD	Strongly Disagree

Microgravity - Teacher's Guide With Activities for Physical Science

1. The teaching guide is easily integrated into the curriculum. SA A D SD
2. The procedures for the activities have sufficient information and are easily understood. SA A D SD
3. The illustrations are adequate to explain the procedures and concepts. SA A D SD
4. Activities effectively demonstrate concepts and are appropriate for the grade level I teach. SA A D SD
5. a. What features of the guide are particularly helpful in your teaching?

   _____

   b. What changes would make the guide more effective for you?

   _____
6. I teach _____ grade. Subjects _____
7. I used the guide with _____ (number of) students.

Additional comments: _____

_____

Today's date: _____

EG-103 December 1995

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